DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

INTRODUCTION

GENERALIZED ACCRETIONARY AND TECTONIC FEATURES OF THE NORTHEAST QUADRANT OF THE CIRCUM-PACIFIC REGION

The concept that a large part of the North American Cordillera is a tectonic collage of allochthonous terranes that were accreted to the North American craton during Mesozoic time as a result of seafloor spreading (Coney and others, 1980; Silberling and Jones, 1984; Howell and others, 1985) is now becoming widely accepted. Most of the accreted terranes are either oceanic or island-arc crust, but some are fragments of continental crust. Boundaries between the accreted terranes and the craton and between individual accreted terranes are commonly high-angle faults. However, some boundaries are essentially horizontal, like the Roberts Mountains thrust in Nevada. Individual terranes have their own distinctive stratigraphy, structural history, and mineral deposits that differ markedly from those of adjoining terranes. Biostratigraphic and paleomagnetic data indicate that some accreted terranes have traveled far from their places of origin, and rotation of as much as 90° is common (Beck and others, 1980). Recognition that a substantial part of the North American Cordillera is a collage of accreted terranes has shed much light on its tectonic evolution and has provided insights into understanding the distribution and genesis of its mineral deposits (Albers, 1981, 1983; Campa and Coney, 1983).

East of the accreted terranes, and in places beneath the allochthons of accreted terranes, is a belt of miogeoclinal sedimentary rocks, chiefly of Paleozoic age. In most places these rocks are folded and were thrust in imbricate style eastward over platform rocks of the craton during the Sevier orogeny (Coney and Reynolds, 1977). This belt of miogeoclinal rocks is continuous from Alaska to southeastern Mexico and, like each of the major types of accreted terranes, is characterized by its own mineral deposit signature.

A large part of the west-central United States is occupied by the Colorado Plateau, a large, high-standing, relatively undisturbed block that is partly bounded by high-angle faults. Precambrian rocks are well exposed, particularly around the periphery of the block. About 100 km east and northeast of the Colorado Plateau the Rocky Mountain front forms the east boundary of the cordillera and marks the approximate eastern limit of the region affected by the Laramide orogeny (80–40 Ma) (Coney and Reynolds, 1977; Dickinson and Snyder, 1978).

A structural style similar to that of the cordilleran disrupted belt is present elsewhere in the United States in the Marathon uplift of western Texas, in the Quachita Mountains farther east, in the southern Appalachians, and also in northwestern South America. Thrusting that involves miogeoclinal and platform rocks in all of the above areas is directed toward the cratonal block.

This interpretive study is intended to complement and extend the basic data depicted on the 1:10,000,000-scale mineral-resources map of the northeast quadrant of the Circum-Pacific thematic map series (Drummond, 1984).

PURPOSE, METHODS, AND GENERAL FEATURES OF THE METALLOGENIC MAPS

The 1:20,000,000-scale metallogenic maps shown here are intended to provide an interpretative overview of the spatial relation of 25 major types of mineral deposits to the accreted terranes and cratonal rocks in the northeast Circum-Pacific quadrant.

The basic procedure was to prepare maps on transparent film that showed the distribution and relative size of individual types of deposits at a scale of 1:5,000,000. The principal sources used in the compilation were the metallogenic maps of North America by Guild (1981) and Dawson (1984), supplemented by additional data from other sources. Only deposits that have a record of production or that have a demonstrated potential for producing a mineral product were considered in the analysis. The transparency for a particular type of deposit was superposed on a map of the same scale showing the accreted terranes and craton, and lines were drawn enclosing groups of deposits that are fairly closely spaced or that appear to be distributed along linear belts. On the maps, solid lines are used to indicate points of control by one or more deposits, and dotted lines indicate our projection between control points. Linear trends of some types of deposits, such as massive sulfides, are clearly restricted to, and controlled by, specific terranes or types of terranes. Linear trends of other types of deposits, such as porphyry copper, cross terrane and craton boundaries and appear to be controlled by other factors, such as megafracture systems and the position of subducting slabs during partial melting events. Whatever the geologic causes controlling the distribution of a deposit type, we wish to emphasize that the areas delineated as favorable by the dotted projections on the maps are based primarily on our interpretation of the distribution of known deposits, supplemented by generally well-known empirical observations that discrete types of deposits are favored by specific types of rock structures, or magmatic association. The results show that individual terranes are typically characterized by one or more specific deposit types or, in some cases, by no deposits. For example, certain accreted island-arc terranes are characterized by massive sulfide deposits, whereas other arc terranes may contain an abundance of skarn iron deposits, or perhaps gold quartz veins. The 1:20,000,000-scale maps on this sheet do not show individual terranes. Instead, all similar terrane types, such as island-arc terranes, are grouped together in order to form coherent cartographic units that can be readily recognized at the map scale.

The maps show that of the 25 types of deposits depicted 6 are characteristic of accreted oceanic or island-arc terranes and 11 are strongly characteristic of cratonal rocks. Eight deposit types are not confined to a particular terrane type over the length of the cordillera but may have a tendency to be restricted to one particular type of terrane within large regions. The grouping of the major types of accreted terranes (for example, oceanic and island arc) unfortunately obscures the relation of deposit types to specific tectonostratigraphic terranes as described above. Similarly, the spatial relation of many deposits to small plutons and important lineaments, whether in accreted terranes or the craton, could not be satisfactorily depicted at this map scale, although the east-northeast orientation of some mineral belts in the craton is a broad reflection of some of these features, particularly lineament control. The grouping of deposit types on the individual maps is for cartographic convenience only and has no genetic connotation. The text accompanying each map discusses distinctive features of the types of deposits and their distribution, gives pertinent information on the age of the deposits, and in most cases includes a brief discussion of the possible source or sources of the metals.

Except in Alaska, a striking feature of mineral belts in accreted terranes is their tendency to parallel the trend of host terranes or the trend of a particular host bed or zone within host terranes. Although mineral belts in the craton show a similar alignment, they also show a definite east-northeast trend in the western conterminous United States and in the Canadian shield. In the latter area, this trend clearly reflects the trend of the greenstone belts, with which the majority of deposits in the shield are associated. The east-northeast trend of mineral belts in the western United States may in part reflect concealed basement trends, but we believe this alignment reflects control by major extensional fracture systems that existed in a region at the time specific deposits were being formed.

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OTHER SOURCES OF INFORMATION AND ACKNOWLEDGMENTS

Unpublished map showing distribution of mineral deposits of Mexico provided by courtesy of Guillermo Salas of Consejo de Recursos Minerales, Mexico City.

Alaska Mineral Resource Assessment Program—USGS open-file maps of various Alaskan 1:250,000-scale quadrangles showing distribution of mineral deposits.

Detailed information on mineral deposits for California and Nevada in the files of authors, supplied mainly by USGS colleagues familiar with some of the recently discovered deposits.

Information on location and size of 70 mineral deposits in northern South America provided by Jose Corvalan of Chile.

Distribution of oil, gas, coal, and oil-shale deposits is greatly simplified from Circum-Pacific Northeast Quadrant Energy-Resource map.

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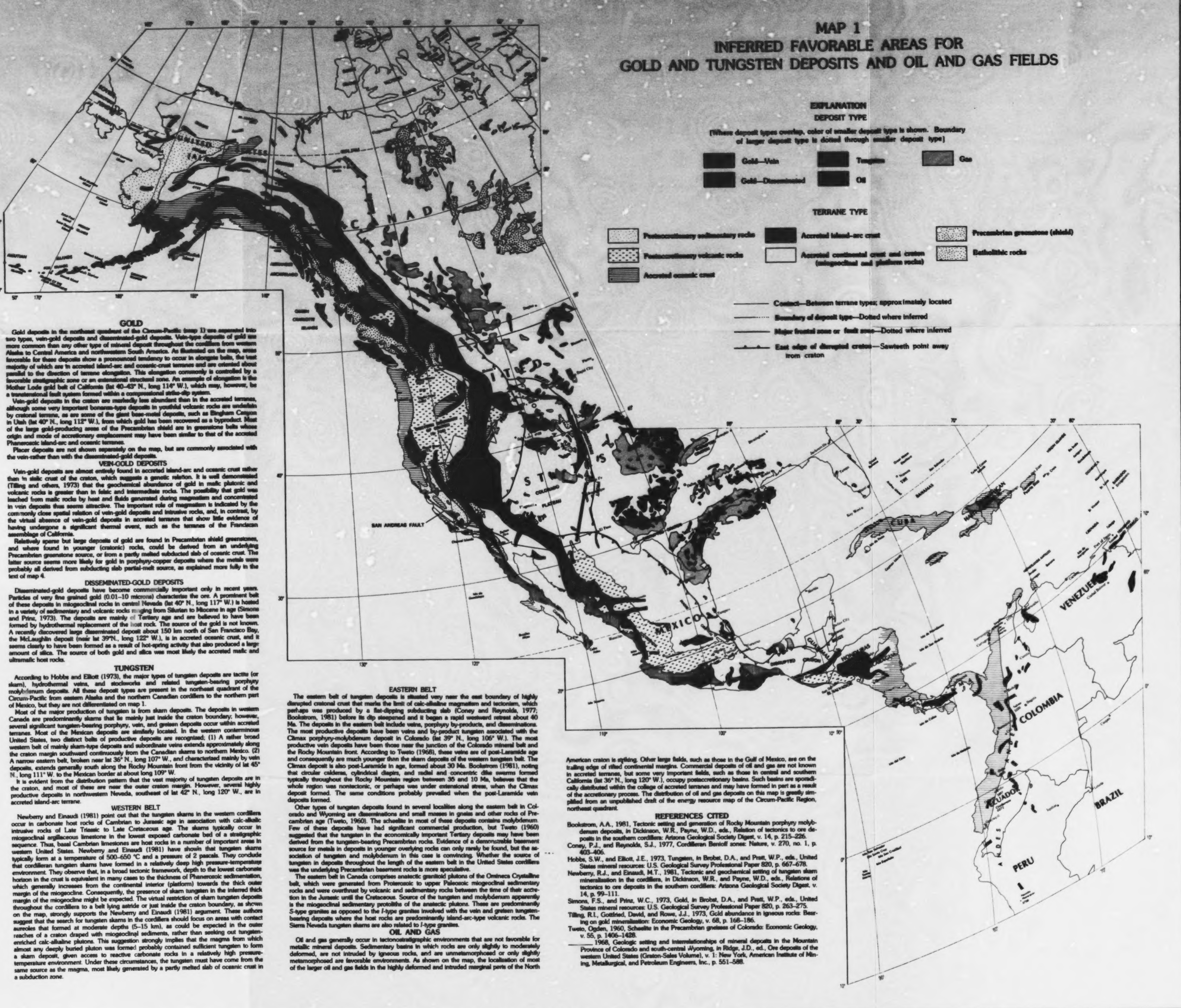
MAP 1
INFERRED FAVORABLE AREAS FOR GOLD AND TUNGSTEN DEPOSITS AND OIL AND GAS FIELDS


EXPLANATION
DEPOSIT TYPE
[Where deposit types overlap, color of smaller deposit type is shown. Boundary of larger deposit type is dotted through smaller deposit type]
Gold—Vein
Gold—Disseminated
Tungsten
Oil
Gas
TERRANE TYPE
Postaccretionary sedimentary rocks
Postaccretionary volcanic rocks
Accreted oceanic crust
Accreted island-arc crust
Accreted continental crust and craton (miogeoclinal and platform rocks)
Precambrian greenstone (shield)
Batholithic rocks
Contact—Between terrane types; approximately located
Boundary of deposit type—Dotted where inferred
Major frontal zone or fault zone—Dotted where inferred
East edge of disrupted craton—Sawteeth point away from craton
CANADA
UNITED STATES (ALASKA)
STATES
MEXICO
SAN ANDREAS FAULT
CUBA
HONDURAS
NICARAGUA
GUATEMALA
EL SALVADOR
VENEZUELA
COLOMBIA
ECUADOR
PERU
BRAZIL
ALEUTIAN
180°
170°
150°
130°
120°
110°
100°
90°
70°
60°
50°
40°
30°
20°
10°
0°

GOLD

Gold deposits in the northeast quadrant of the Circum-Pacific (map 1) are separated into two types, vein-gold deposits and disseminated-gold deposits. Vein-type deposits of gold are more common than any other type of mineral deposit throughout the cordillera from western Alaska to Central America and northwestern South America. As illustrated on the map, areas favorable for these deposits show a pronounced tendency to occur in elongate belts, the vast majority of which are in accreted island-arc and oceanic-crust terranes and are oriented about parallel to the direction of terrane elongation. This elongation commonly is controlled by a favorable stratigraphic zone or an extensional structural zone. An example of elongation is the Mother Lode gold belt of California (lat 40–43° N., long 114° W.), which may, however, be a transtensional fault system formed within a compressional strike-slip system.

Vein-gold deposits in the craton are markedly less abundant than in the accreted terranes, although some very important bonanza-type deposits in youthful volcanic rocks are underlain by cratonal terrane, as are some of the giant base-metal deposits, such as Bingham Canyon in Utah (lat 40° N., long 112° W.), from which gold has been recovered as a byproduct. Most of the large gold-producing areas of the Precambrian shield are in greenstone belts whose origin and mode of accretionary emplacement may have been similar to that of the accreted Phanerozoic island-arc and oceanic terranes.

Placer deposits are not shown separately on the map, but are commonly associated with the vein-rather than with the disseminated-gold deposits.

VEIN-GOLD DEPOSITS

Vein-gold deposits are almost entirely found in accreted island-arc and oceanic crust rather than in sialic crust of the craton, which suggests a genetic relation. It is well demonstrated (Tilling and others, 1973) that the geochemical abundance of gold in mafic plutonic and volcanic rocks is greater than in felsic and intermediate rocks. The possibility that gold was leached from mafic rocks by heat and fluids generated during magmatism and concentrated in vein deposits thus seems attractive. The important role of magmatism is indicated by the commonly close spatial relation of vein-gold deposits and intrusive rocks, and, in contrast, by the virtual absence of vein-gold deposits in accreted terranes that show little evidence of having undergone a significant thermal event, such as the terranes of the Franciscan assemblage of California.

Relatively sparse but large deposits of gold are found in Precambrian shield greenstones, and where found in younger (cratonic) rocks, could be derived from an underlying Precambrian greenstone source, or from a partly melted subducted slab of oceanic crust. The latter source seems more likely for gold in porphyry-copper deposits where the metals were probably all derived from subducting slab partial-melt source, as explained more fully in the text of map 4.

DISSEMINATED-GOLD DEPOSITS

Disseminated-gold deposits have become commercially important only in recent years. Particles of very fine grained gold (0.01–10 microns) characterize the ore. A prominent belt of these deposits in miogeoclinal rocks in central Nevada (lat 40° N., long 117° W.) is hosted in a variety of sedimentary and volcanic rocks ranging from Silurian to Miocene in age (Simons and Prinz, 1973). The deposits are mainly of Tertiary age and are believed to have been formed by hydrothermal replacement of the host rock. The source of the gold is not known. A recently discovered large disseminated deposit about 150 km north of San Francisco Bay, the McLaughlin deposit (near lat 39°N., long 122° W.), is in accreted oceanic crust, and it seems clearly to have been formed as a result of hot-spring activity that also produced a large amount of silica. The source of both gold and silica was most likely the accreted mafic and ultramafic host rocks.

TUNGSTEN

According to Hobbs and Elliott (1973), the major types of tungsten deposits are tactite (or skarn), hydrothermal veins, and stockworks and related tungsten-bearing porphyry molybdenum deposits. All these deposit types are present in the northeast quadrant of the Circum-Pacific from eastern Alaska and the northern Canadian cordillera to the northern part of Mexico, but they are not differentiated on map 1.

Most of the major production of tungsten is from skarn deposits. The deposits in western Canada are predominantly skarns that lie mainly just inside the craton boundary; however, several significant tungsten-bearing porphyry, vein, and greisen deposits occur within accreted terranes. Most of the Mexican deposits are similarly located. In the western conterminous United States, two distinct belts of productive deposits are recognized: (1) A rather broad western belt of mainly skarn-type deposits and subordinate veins extends approximately along the craton margin southward continuously from the Canadian skarns to northern Mexico. (2) A narrow eastern belt, broken near lat 36° N., long 107° W., and characterized mainly by vein deposits, extends generally south along the Rocky Mountain front from the vicinity of lat 45° N., long 111° W. to the Mexican border at about long 109° W.

It is evident from the distribution pattern that the vast majority of tungsten deposits are in the craton, and most of these are near the outer craton margin. However, several highly productive deposits in northwestern Nevada, southeast of lat 42° N., long 120° W., are in accreted island-arc terrane.

WESTERN BELT

Newberry and Einaudi (1981) point out that the tungsten skarns in the western cordillera occur in carbonate host rocks of Cambrian to Jurassic age in association with calc-alkalic intrusive rocks of Late Triassic to Late Cretaceous age. The skarns typically occur in miogeoclinal argillaceous limestone in the lowest exposed carbonate bed of a stratigraphic sequence. Thus, basal Cambrian limestones are host rocks in a number of important areas in western United States. Newberry and Einaudi (1981) have shown that tungsten skarns typically form at a temperature of 500–650 °C and a pressure of 2 pascals. They conclude that cordilleran tungsten skarns have formed in a relatively deep high pressure-temperature environment. They observe that, in a broad tectonic framework, depth to the lowest carbonate horizon in the crust is equivalent in many cases to the thickness of Phanerozoic sedimentation, which generally increases from the continental interior (platform) towards the thick outer margin of the miogeocline. Consequently, the presence of skarn tungsten in the inferred thick margin of the miogeocline might be expected. The virtual restriction of skarn tungsten deposits throughout the cordillera to a belt lying astride or just inside the craton boundary, as shown on the map, strongly supports the Newberry and Einaudi (1981) argument. These authors suggest that the search for tungsten skarns in the cordillera should focus on areas with contact aureoles that formed at moderate depths (5–15 km), as could be expected in the outer reaches of a craton draped with miogeoclinal sediments, rather than seeking out tungsten-enriched calc-alkaline plutons. This suggestion strongly implies that the magma from which almost any deeply buried pluton was formed probably contained sufficient tungsten to form a skarn deposit, given access to reactive carbonate rocks in a relatively high pressure-temperature environment. Under these circumstances, the tungsten must have come from the same source as the magma, most likely generated by a partly melted slab of oceanic crust in a subduction zone.

EASTERN BELT

The eastern belt of tungsten deposits is situated very near the east boundary of highly disrupted cratonal crust that marks the limit of calc-alkaline magmatism and tectonism, which perhaps was produced by a flat-dipping subducting slab (Coney and Reynolds, 1977; Bookstrom, 1981) before its dip steepened and it began a rapid westward retreat about 40 Ma. The deposits in the eastern belt include veins, porphyry by-products, and disseminations. The most productive deposits have been veins and by-product tungsten associated with the Climax porphyry-molybdenum deposit in Colorado (lat 39° N., long 106° W.). The most productive vein deposits have been those near the junction of the Colorado mineral belt and the Rocky Mountain front. According to Tweto (1968), these veins are of post-Laramide age and consequently are much younger than the skarn deposits of the western tungsten belt. The Climax deposit is also post-Laramide in age, formed about 30 Ma. Bookstrom (1981), noting that circular calderas, cylindrical diapirs, and radial and concentric dike swarms formed typically throughout the Rocky Mountain region between 38 and 10 Ma, believes that the whole region was nontectonic, or perhaps was under extensional stress, when the Climax deposit formed. The same conditions probably prevailed when the post-Laramide vein deposits formed.

Other types of tungsten deposits found in several localities along the eastern belt in Colorado and Wyoming are disseminations and small masses in gneiss and other rocks of Precambrian age (Tweto, 1960). The scheelite in most of these deposits contains molybdenum. Few of these deposits have had significant commercial production, but Tweto (1960) suggested that the tungsten in the economically important Tertiary deposits may have been derived from the tungsten-bearing Precambrian rocks. Evidence of a demonstrable basement source for metals in deposits in younger overlying rocks can only rarely be found, but the association of tungsten and molybdenum in this case is convincing. Whether the source of tungsten in deposits throughout the length of the eastern belt in the United States cordillera was the underlying Precambrian basement rocks is more speculative.

The eastern belt in Canada comprises anatectic granitoid plutons of the Omineca Crystalline belt, which were generated from Proterozoic to upper Paleozoic miogeoclinal sedimentary rocks and were overthrust by volcanic and sedimentary rocks between the time of their accretion in the Jurassic until the Cretaceous. Source of the tungsten and molybdenum apparently is the miogeoclinal sedimentary protoliths of the anatectic plutons. These are predominantly *S*-type granites as opposed to the *I*-type granites involved with the vein and greisen tungsten-bearing deposits where the host rocks are predominantly island-arc-type volcanic rocks. The Sierra Nevada tungsten skarns are also related to *I*-type granites.

OIL AND GAS

Oil and gas generally occur in tectonostratigraphic environments that are not favorable for metallic mineral deposits. Sedimentary basins in which rocks are only slightly to moderately deformed, are not intruded by igneous rocks, and are unmetamorphosed or only slightly metamorphosed are favorable environments. As shown on the map, the localization of most of the larger oil and gas fields in the highly deformed and intruded marginal parts of the North American craton is striking. Other large fields, such as those in the Gulf of Mexico, are on the trailing edge of rifted continental margins. Commercial deposits of oil and gas are not known in accreted terranes, but some very important fields, such as those in central and southern California (lat 36° N., long 120° W.), occupy postaccretionary basins. Such basins are sporadically distributed within the collage of accreted terranes and may have formed in part as a result of the accretionary process. The distribution of oil and gas deposits on this map is greatly simplified from an unpublished draft of the energy resource map of the Circum-Pacific Region, northeast quadrant.

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MERCURY

Mercury deposits in the northeast quadrant of the Circum-Pacific are almost completely restricted to accreted oceanic or island-arc terranes, or to postaccretionary rocks overlying such terranes. A few small deposits in Mexico, Alaska, and the western United States are in continental crust which in Mexico is thought to be accreted and not part of the craton. Mercury deposits are commonly found in tectonically active areas that have had Tertiary or Quaternary thermal activity indicated by volcanic rocks and hot springs.

Several types of mercury deposits are represented (but not differentiated) on the map. The largest producing area is in the Coast Ranges of California (lat 39° N., long 112° W.) where at least half the deposits are of the silica-carbonate type (Davis and Bailey, 1966) associated with serpentinite. Deposits in western Canada are also mainly silica-carbonate type. Other principal deposit types are opalite, associated with Cenozoic volcanic rocks and common in parts of the Basin-Range region of the western United States, and veins in fault and shear zones cutting diverse types of rocks. All mercury deposits in the cordillera are geologically young; probably none are older than the late Oligocene. Deposits are less abundant in western Canada and Alaska than in the western United States, and are rare in Central America and northwestern South America.

A large area of small but productive mercury deposits lies astride lat 40° N. and east of long 120° W. The mercury occurs in a wide variety of rocks and in different types of deposits, but is primarily associated with silicic and intermediate volcanic rocks of Tertiary age. Most mercury deposits are located west of the $^{87}Sr/^{86}Sr = 0.706$ (craton boundary) line (Kistler, 1983) in accreted terranes, and most deposits show a marked alignment along northwest and northeast trends, indicating probable distributional control by fracture systems. Most deposits in Canada are postaccretionary and related to late movement on major faults, probably with accompanying epithermal or geothermal activity.

Although mercury deposits in the northeast quadrant are decidedly hosted in accreted oceanic or island-arc crust, the same relation is not found in other parts of the world. Bailey and others (1973) point out that, based on world-wide relations, almost any kind of rock may be the host, and they make a strong case relating mercury deposits to post-Jurassic subduction zones. They indicate that deposits are localized where oceanic crust has been subducted and speculate that mercury originally contained in subducted trench sediments, or in the subducted oceanic crust, "* * * was distilled out of the downward plunging plate and emplaced at a higher cooler level along or above the subduction zone." White (1967) had earlier proposed that eugeosynclinal sedimentary rocks might be the source of the mercury in some deposits in California. It seems fairly clear that the types of rock from which mercury can be readily leached or distilled in sufficient quantities to yield an ore deposit are of oceanic and not continental affiliation, whatever the type of terrane the mercury deposit is in.

URANIUM

Although uranium is commonly present in accreted terranes as well as in the craton, nearly all known deposits having commercial value are in platform and shield segments of the craton. More than 90 percent of Canadian deposits are in the western and southern parts of the Precambrian shield (Lang, 1952). These uranium deposits are primarily epigenetic vein-like deposits, which according to Ruzicka (1971), were initially formed mainly as uraninite (pitchblende) deposits during several mineralizing episodes between 2,600 and 1,000 Ma. Lang (1952) reports that basic rocks including amphibolite, basalt, and diabase dikes are the favorable host rocks for many uranium deposits, but believes the source of the uranium was "acid" magmas. Ruzicka (1971) concurs with this belief but adds that argillaceous sediments might also be a source.

Most of the vein deposits in the Precambrian shield of central Canada are localized along faults, shear zones, fracture systems, and igneous contacts (Lang, 1952); and Lang (1970), observing the dominance of northeast trends, postulates a series of northeast-trending lineaments, some 1,500 km long. A number of these postulated northeast-trending lineaments are within and follow the trend of greenstone belts.

In the western United States most uranium deposits of commercial value are epigenetic sedimentary deposits hosted by lenticular sandstone beds that range in age from the middle Paleozoic to the Pliocene (Finch, 1967; Young, 1978). The major host sandstones are of Triassic and Jurassic age. Most deposits are tabular layers that nearly parallel bedding (Finch, 1967). The host sandstones are thought to have formed mainly in continental environments such as successor basins, shallow depressions, intermontane basins, and coastal plains. Closely related to these peneconcordant epigenetic deposits are discordant "roll" and vein deposits that represent uranium derived from host sandstones and redistributed, mainly by oxygenated ground waters.

Uranium deposits in the western United States show a wide variation in isotopic ages. Data presented by Finch (1967) for 12 Colorado Plateau deposits show lead ages ranging from about 295 to 54 Ma. Rosenburg and Hooper (1982) report fission-track ages of about 6.7 Ma for redistributed sandstone-hosted uranium ore in the Grants mineral belt, New Mexico (lat 35° N., long 107° W.), and ages as young as 11,000–150,000 years are reported for some unoxidized uranium minerals in Wyoming north of lat 40° N. (Finch, 1967).

Of the numerous hypotheses that have been proposed for the origin of the sandstone-hosted uranium, it appears that Gruner's (1956) thesis of multiple migration-accretion, endorsed by Garrels (1957) and Finch (1967), best fits the widespread distribution of uranium and the scarcity of igneous rocks that characterize the epigenetic uranium deposits. This hypothesis holds that the source of uranium was the large volume of Precambrian rocks that were eroded in post-Pennsylvanian time, which could have provided at least 400 million tons of uranium. Gruner (1956) believes that given an interior basin environment, arid or semiarid conditions, and no access to the sea, this uranium could have been leached by Ca, Mg, or Na bicarbonates, and carried long distances in CO_2-rich groundwaters to sites where reducing conditions were met. Concentration of large deposits of uranium could result, according to Gruner, from several stages of oxidation-solution-migration-accretion.

The abundance of uranium and the similarity in age and lithology of Precambrian host rocks in the Canadian shield and the Rocky Mountain front range noted by Nash and others (1981) suggest the continuation of similar, probably uranium-rich Precambrian terranes beneath the western United States and seems to strongly support Gruner's thesis that the primary source of uranium is Precambrian rocks. Moreover, the mechanism they propose for its leaching, transport, and deposition explains convincingly the extremely broad distribution of sandstone-hosted deposits as well as the wide variation in their ages.

LEAD AND ZINC

Four main types of lead-zinc deposits are shown on the map. One is sediment-hosted exhalative massive sulfides, of which the Sullivan deposit in southern British Columbia, near lat 50° N., long 116° W., is perhaps the best known North American example. A second type is the mainly carbonate-hosted deposits such as in the western United States at Metaline, Wash., Tintic, Utah, and Darwin, Calif. Vein deposits typified by those of the Coeur d'Alene district of Idaho (lat 47° N., long 116° W.), and replacement (skarn, manto, chimney) deposits of the Sierra Madre Oriental in Mexico constitute a third major type. Volcanogenic massive sulfide deposits, mainly in the Canadian shield, that have yielded zinc and lead as the principal metals represent a fourth type. Only the first two types of lead-zinc deposits are discussed in this section.

SEDIMENT-HOSTED LEAD-ZINC DEPOSITS

Most of the known sediment-hosted (exhalative) massive sulfide lead-zinc deposits in the North America Cordillera are in British Columbia, the Northwest Territories, Yukon, and Alaska. Others occur in the vicinity of lats 43° and 44° N., and long 115° W. in the United States, but none have been identified south of the Snake River Plain (about lat 42°N.). The sediment-hosted massive sulfide deposits are restricted to the craton in Canada, but the deposits near long 115° W. in the United States are in allochthonous accreted sedimentary rocks. The Sullivan ore body, described by Hamilton and others (1983), is close to the craton boundary in silicastone rocks of Middle Proterozoic age. MacIntyre (1983) describes similar deposits in the Gataga district of northeastern British Columbia (not shown on map) as being hosted in lower Paleozoic deep-marine clastic sedimentary rocks that accumulated in structurally controlled basins and troughs located along the west margin of the North American craton from Cambrian to Late Devonian time.

According to an empirical model developed by Large (1983), the typical host environment for this deposit type is an epicrantonic basin bounded by high-angle faults on one or both sides. Subsidence of the basin was controlled by faulting, and the mineral deposits are commonly close to these fault zones. First, second, and third order basins are recognized by Large (1983). The third order basins are smallest, measuring only a few hundred meters to a few kilometers in lateral extent, and are the morphological traps in which the stratiform sulfides accumulated. Many of the deposits contain abundant barite and chert as well as the sulfide ore minerals, and most contain significant amounts of silver. The deposits formed synchronously with their enclosing sediments at the time of basin sedimentation and result probably from hydrothermal fluids circulating in a convection cell and issuing as metal-laden brines from tectonically controlled discharge vents on the seafloor.

Inasmuch as the exhalative massive-sulfide deposits formed syngenetically with sedimentary rocks ranging in age from Middle Proterozoic to Carboniferous, they predate any recognized accretionary (compressional) episode in the western cordillera. Their morphology and depositional environment suggest formation in an extensional tectonic regime punctuated by episodes of rifting, a condition that Hutchinson (1980) noted was characteristic of Middle Proterozoic, and which may have persisted until the middle Paleozoic.

MANGANESE

Manganese deposits in the western cordillera of North America are largely but not entirely restricted to the area between lat 17° N. in Mexico and lat 50° N. in southern Canada. Outside the cordillera, the main deposits of significance are in Cuba.

The deposits are grouped into three types, following the terminology of Dorr and others (1973)—volcanogene (manganiferous chert), sedimentary, and hypogene (vein). The three types are to some extent intergradational, and all are modified to some degree by supergene processes. The volcanogene deposits, are characteristic of accreted oceanic-crust terranes where most such deposits are found. They are typically in discrete layers within thick piles of volcanic rocks and may be either sharply lenticular or stratiform (Dorr and others, 1973). Many deposits of this type in the California Coast Ranges and elsewhere are associated with chert and consist largely of manganese silicate minerals. Other areas containing volcanogene deposits are in the Washington Olympic Peninsula south of the lat 48° N. and in western Mexico and eastern Cuba close to lat 20° N.

The sedimentary manganese deposits may be oxides or carbonates. Most of the large bedded manganese deposits of the world are marine sedimentary deposits of Precambrian age, but those in the Circum-Pacific northeast quadrant are probably late Phanerozoic in age and associated with fresh water lake beds. The most productive deposit of this type is the Molango (carbonate) deposit, located in continental crust rocks, about lat 21° N. in eastern Mexico. Other fairly large deposits of lower grade are found in the craton near lat 34° N. in southwestern United States.

Hypogene deposits are mostly veins restricted to the craton, including postaccretionary volcanic rocks in the craton. A few replacement deposits are found in the western United States, such as the Leadville deposit in Colorado and the Philipsburg deposit in Montana. Overall production from these deposits has been small, and in many of the hypogene deposits manganese is accompanied by base and/or precious metals.

Dorr and others (1973) state that the source of manganese in all these deposits was either manganiferous mafic minerals in igenous rocks, or manganese enriched magmas, but much disagreement exists as to the relative importance of these sources and as to the number and kinds of concentration processes to which the manganeses has been subjected. However, it appears that the ultimate source of manganese in nodules on the Pacific Ocean seafloor was probably volcanic. Moreover, restriction of land-based deposits in postaccretionary rocks in the cordillera to the area almost directly east ("downstream" as it were) of the subducting nodule-laden Pacific Ocean floor indicates manganese enrichment of oceanic volcanic rocks.

FLUORSPAR

Fluorspar vein deposits in the western cordillera are almost entirely in the craton. They are present in the region between lats 21° N. and 60° N. There are apparently no known fluorspar deposits in Alaska, southern Mexico, and Central America, but a fairly well defined belt of small deposits is present in cratonal rocks of Colombia.

In the western United States, Lamarre and Hodder (1978) describe two curvilinear belts of fluorspar deposits—a western and an eastern belt. Their western belt seems to be based mainly on small occurrences; productive deposits are widely spaced, and consequently we do not include their western belt as a continuous belt on the map. However, their eastern belt corresponds closely with our well-defined fluorspar belt, which extends from approximately lat 42° N., long 106° W. southward to central Mexico.

Van Alstine (1976) argues that major fluorspar deposits are localized chiefly near continental rift zones and lineaments, a contention well supported by the 45 fluorspar deposits associated with the Rio Grande graben, a principal part of the eastern belt.

Lamarre and Hodder (1978) and Cumming and others (1979) observed that fluorspar deposits in the western United States and in northern Mexico are spatially associated with alkalic igneous rocks and are middle and late Tertiary in age. According to Lamarre and Hodder (1978), two fluorspar belts "are situated above the deepest parts of the two postulated early to middle Tertiary subduction zones. * * * Fluorine may have been concentrated in alkalic magmas generated along these subducton zones, carried through the crust as SiF_4, and deposited as CaF_2." In Lamarre and Hodder's view, the fluorine was derived from mineral components of the slab through processes related to partial melting of a subducting slab of oceanic lithosphere.

On the other hand, Clark and others (1982) show high initial strontium-isotope ratios in alkalic intrusions spatially related to fluorspar deposits in the Trans Pecos of west Texas. They believe such ratios strongly suggest crustal contamination of the alkalic magmas, possibly from underlying Precambrian rocks, and they imply that fluorine from these rocks may have enriched the alkalic magmas.

IRON

Iron skarns (contact metasomatic deposits) are prominent in island-arc terranes in southwestern and southern Alaska, western British Columbia, western Nevada, and Mexico, but important deposits are found also in cratonal rocks in southwestern Utah and southeastern California. Iron skarn deposits have not been reported in Central America where island-arc terranes are rare. The conspicuous presence of such skarns in island-arc terranes above former sites of partly melted subducted slabs is to be expected, and skarn deposits in continental crust doubtless resulted from subduction events beneath the craton. The iron in the continental crust deposits may have been derived either from partial melting of a slab, or alternatively, from iron-rich Precambrian crustal rocks within the zone of thermal activity.

The iron skarn deposits of the western cordillera range in age from mid-Permian to late Oligocene or early Miocene. The oldest deposits are associated with 260 Ma old granitoid bodies in northern California. Next oldest are the skarns of British Columbia (Sangster, 1969), related to intrusive rocks mainly of Middle and Late Jurassic age. The Mexican skarns are apparently related mainly to Early Cretaceous igneous rocks, although some may be as young as Eocene. Skarns in Vancouver Island, British Columbia, are preaccretionary in age with respect to their Cretaceous island-arc host terrane. Skarns in southeastern California and western Nevada (Reeves and Kral, 1955; Reeves and others, 1958) are chiefly Late Cretaceous in age, while those in northern Nevada are Eocene or Oligocene in age (Shawe and others, 1962). The youngest skarns are in the Iron Springs district of Utah where laccolithic quartz monzonite bodies of late Oligocene or early Miocene age intrude Jurassic limestone (Klemic and others, 1973). Skarns were apparently produced during at least half a dozen thermal events in western North America over a span of time exceeding 230 Ma.

Sedimentary iron deposits occur in rocks of Precambrian and Phanerozoic age, and nearly all such deposits are in the craton. Significant deposits of sedimentary iron occur in Late Proterozoic and Cretaceous sedimentary rocks of northern Yukon.

SCALE 1:20 000 000

400 0 400 800 1200 1600 2000 2400 KILOMETERS

400 0 400 800 1200 1600 MILES

METALLOGENIC MAPS OF THE NORTHEAST QUADRANT OF THE CIRCUM-PACIFIC REGION, SHOWING INFERRED MINERAL BELTS AND DISTRIBUTION OF OIL AND GAS FIELDS IN ACCRETED TERRANES AND CRATON

By

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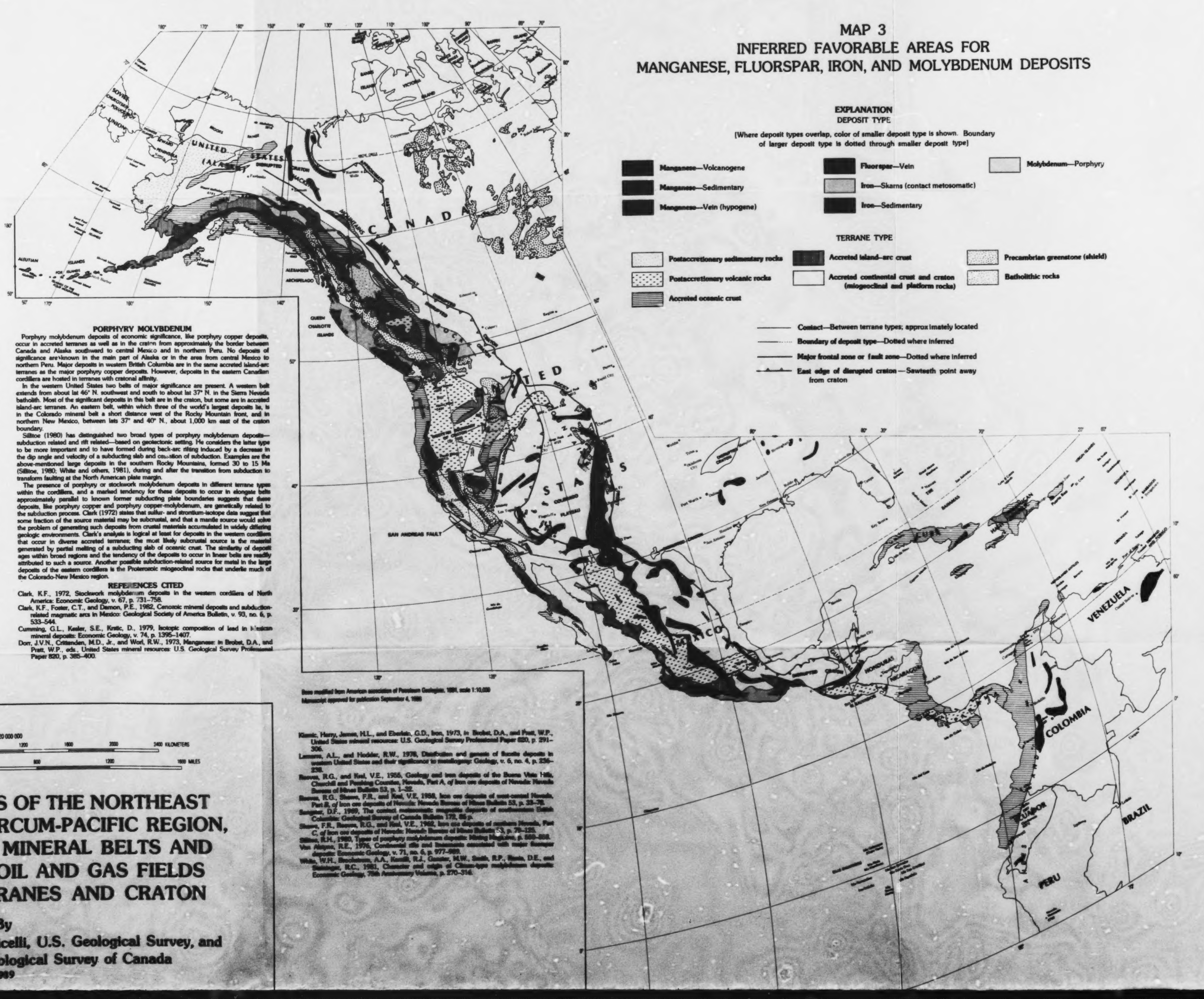
1989

MAP 3
INFERRED FAVORABLE AREAS FOR MANGANESE, FLUORSPAR, IRON, AND MOLYBDENUM DEPOSITS


EXPLANATION
DEPOSIT TYPE
[Where deposit types overlap, color of smaller deposit type is shown. Boundary of larger deposit type is dotted through smaller deposit type]
Manganese—Volcanogene
Manganese—Sedimentary
Manganese—Vein (hypogene)
Fluorspar—Vein
Iron—Skarns (contact metasomatic)
Iron—Sedimentary
Molybdenum—Porphyry
TERRANE TYPE
Postaccretionary sedimentary rocks
Postaccretionary volcanic rocks
Accreted oceanic crust
Accreted island-arc crust
Accreted continental crust and craton (miogeoclinal and platform rocks)
Precambrian greenstone (shield)
Batholithic rocks
Contact—Between terrane types; approximately located
Boundary of deposit type—Dotted where inferred
Major frontal zone or fault zone—Dotted where inferred
East edge of disrupted craton—Sawteeth point away from craton
SOVIET UNION
UNITED STATES (ALASKA)
DISRUPTED CRATON
CANADA
UNITED STATES
COLORADO PLATEAU
SAN ANDREAS FAULT
ALEUTIAN ISLANDS
ALEXANDER ARCHIPELAGO
QUEEN CHARLOTTE ISLANDS
CUBA
VENEZUELA
COLOMBIA
PERU
BRAZIL
180°
170°
160°
150°
140°
130°
120°
50°
40°
30°
20°
10°
0°

Base modified from American association of Petroleum Geologists, 1981, scale 1:10,000
Manuscript approved for publication September 4, 1986

PORPHYRY MOLYBDENUM

Porphyry molybdenum deposits of economic significance, like porphyry copper deposits, occur in accreted terranes as well as in the craton from approximately the border between Canada and Alaska southward to central Mexico and in northern Peru. No deposits of significance are known in the main part of Alaska or in the area from central Mexico to northern Peru. Major deposits in western British Columbia are in the same accreted island-arc terranes as the major porphyry copper deposits. However, deposits in the eastern Canadian cordillera are hosted in terranes with cratonal affinity.

In the western United States two belts of major significance are present. A western belt extends from about lat 46° N. southwest and south to about lat 37° N. in the Sierra Nevada batholith. Most of the significant deposits in this belt are in the craton, but some are in accreted island-arc terranes. An eastern belt, within which three of the world's largest deposits lie, is in the Colorado mineral belt a short distance west of the Rocky Mountain front, and in northern New Mexico, between lats 37° and 40° N., about 1,000 km east of the craton boundary.

Sillitoe (1980) has distinguished two broad types of porphyry molybdenum deposits—subduction related and rift related—based on geotectonic setting. He considers the latter type to be more important and to have formed during back-arc rifting induced by a decrease in the dip angle and velocity of a subducting slab and cessation of subduction. Examples are the above-mentioned large deposits in the southern Rocky Mountains, formed 30 to 15 Ma (Sillitoe, 1980; White and others, 1981), during and after the transition from subduction to transform faulting at the North American plate margin.

The presence of porphyry or stockwork molybdenum deposits in different terrane types within the cordillera, and a marked tendency for these deposits to occur in elongate belts approximately parallel to known former subducting plate boundaries suggests that these deposits, like porphyry copper and porphyry copper-molybdenum, are genetically related to the subduction process. Clark (1972) states that sulfur- and strontium-isotope data suggest that some fraction of the source material may be subcrustal, and that a mantle source would solve the problem of generating such deposits from crustal materials accumulated in widely differing geologic environments. Clark's analysis is logical at least for deposits in the western cordillera that occur in diverse accreted terranes; the most likely subcrustal source is the material generated by partial melting of a subducting slab of oceanic crust. The similarity of deposit ages within broad regions and the tendency of the deposits to occur in linear belts are readily attributed to such a source. Another possible subduction-related source for metal in the large deposits of the eastern cordillera is the Proterozoic miogeoclinal rocks that underlie much of the Colorado-New Mexico region.

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PORPHYRY COPPER AND PORPHYRY COPPER-MOLYBDENUM DEPOSITS

The porphyry copper deposits, including those containing significant gold, and the porphyry copper-molybdenum deposits, are variants of a single deposit type and are grouped together on map 4. They are generally associated with hypabyssal calc-alkalic intrusions ranging in composition from quartz monzonite to diorite (Hollister, 1978).

It is evident from their distribution from north to south that while the porphyry-type deposits are not characteristic of any one type of terrane over the expanse of the northeast quadrant of the Circum-Pacific, they are nevertheless restricted to individual terrane types within specific large regions. Porphyry deposits in Alaska are in two belts, one in accreted island arc terrane and the other in the craton, whereas the deposits in British Columbia are confined almost entirely to accreted island-arc terranes. The majority of porphyry-type deposits in the western United States and northern Mexico are in the craton; exceptions are deposits at Yerington, Nev. (lat 42° N., long 124° W.), and at Lights Creek, Calif. (lat 39° N., long 120° W.), which are in accreted island-arc terranes. Largely undeveloped porphyry-type deposits in southern Mexico are hosted in island-arc terrane, while those in Panama, Colombia, and Ecuador are in accreted oceanic crust terrane as far south as 4° S. latitude. Beyond that, to the south edge of the map at lat 10° S., several large porphyry copper-molybdenum deposits are in the continental margin magmatic arc of the craton. Although porphyry deposits hosted in each of the three major types of terranes have distinctive geologic features, it is apparent that physical and compositional features of the deposits show a common thread throughout the length of the cordillera, suggesting a similar genesis for the deposits and probably a common source for the metals.

The age of porphyry deposits within the western cordillera ranges from Triassic to the late Tertiary. The age range in the southwestern United States and northern Mexico is remarkably narrow (about 20 Ma), whereas deposits in central British Columbia show an overall range of about 163 Ma and a clustering within perhaps six rather distinct age groups (Christopher and Carter, 1976). The oldest porphyry copper deposits in the northeast quadrant of the Circum-Pacific (British Columbia) formed slightly more than 200 Ma, or about the time of the opening of the Atlantic Ocean, which may indicate a possible genetic relationship between plate movement and the formation of porphyry-type deposits. This time (~200 Ma) is slightly prior to accretion of the host terranes in Early and Middle Jurassic time, therefore, the oldest British Columbia porphyries are preaccretionary in age.

At least 90 percent of the porphyry deposits in the southwestern United States and northern Mexico, and a high percentage of such deposits in British Columbia, the Caribbean, and in the western United States were formed during the Laramide orogeny, a relatively short span of time lasting from about 80 to 40 Ma (Coney, 1976). Age differences within the Laramide interval probably result from migration of a magmatic arc above a shallow, gently-dipping subducting slab.

The marked tendency for the porphyry-type deposits to occur in elongate belts inboard from present or former subducting plate boundaries indicates that these deposits are genetically related to the subduction process. No so easily explained is the tendency for some porphyry-type deposits to occur in clusters in the southwestern United States and central British Columbia, or the occurrence of such isolated very large deposits as those at Butte, Bingham, and Ely in the western United States. The answer to this question may be control by large intersecting fracture systems penetrating the entire thickness of the crust. Also, some porphyry deposits may be buried by young cover rocks, in which case clustering might be only an apparent phenomenon.

Sillitoe (1972) has presented a cogent argument that porphyry deposits constitute a normal facet of calc-alkaline magmatism, and that the components of calc-alkaline igneous rocks and porphyry deposits are generated by partial melting of oceanic crustal rocks in underlying subduction zones at the elongate compressive juncture between lithospheric plates. He argues further that the only source of metals available to all porphyry copper deposits, taking into consideration the thin crust and almost total absence of sialic crust beneath some copper provinces (such as the Solomon Islands), would seem to be the upper mantle, the probable ultimate source of metals in virtually all mineral deposits. Burnham (1981) points out that during metamorphism of oceanic basalt containing an average of 77 parts per million (ppm) copper and 1,000 ppm FeS during subduction, nearly all the copper would combine with the FeS to form a pyrrhotite solid solution that would dissolve and provide an ample source of copper for porphyry deposits upon melting of the amphibolite. Burnham (1981) concludes "it is unnecessary to call upon abnormally copper-rich rocks, such as the metalliferous sediments of the Nazca plate (or copper-rich Precambrian basement rocks), for the sources of ore bearing magmas."

This argument is most convincing for the numerous deposits that lie inboard a reasonable distance (150–250 km) from present or former trenches of subduction zones. However, a rational explanation for distant relatively isolated deposits hundreds of kilometers from such trenches is more elusive. Coney and Reynolds (1977) tracked the systematic variation in the radiometric ages of Cretaceous and Tertiary igneous rocks, and concluded that the dip of the Benioff zone (subducting slab) flattened progressively beneath southwestern North America during the interval beneath 130–110 Ma and about 55–40 Ma. The decrease in dip is believed due to a high rate of convergence—the higher the rate, the lower the angle of dip. If this analysis is correct, the copper and other metals in the great porphyry deposits of Butte, Bingham, and Ely could have come from partial melting of shallow-dipping relatively fast-moving subducting slabs. Further support for this argument is that similarities in general geochemistry of intrusive rocks associated with porphyry copper deposits and style of porphyry copper mineralization in continental terranes, compared to that in island-arc terranes, suggest that the magmas in both types of terranes were probably largely derived beneath the crust, and that continental contamination contributed insignificantly to the magma or metals (Mitchell and Garson, 1981).

One further point worth noting is that, while most deposits of the porphyry type appear in general to be spatially related to a subduction zone and hence to a compressional tectonic regime, it is also evident that a high percentage of porphyry deposits are localized at or near the intersection of important fracture systems, one system commonly being strike slip, and the other extensional dip slip (Hollister, 1978; Titley, 1982). This is further borne out by the presence of abundant dikes closely associated with porphyry copper deposits, which clearly indicates an extensional environment at the time of intrusion and mineralization. The favored structural environment in which many porphyry systems were emplaced would thus appear to be tensional, at least at the level of emplacement.

TIN

Deposits of tin in the northeast quadrant of the Circum-Pacific are sparse, widely scattered, and small. The few deposits that have produced tin are widely separated localities from the Seward Peninsula in Alaska to central Mexico. Some tin has been produced as a by-product in the production of other metals, mainly from the Sullivan lead-zinc mine in southern Canada (lat 50° N.). All the deposits that have produced tin are in the craton, but unproductive occurrences of tin are present in accreted terranes as well as in the craton.

Sainsbury and Reed (1973) observe that tin deposits are typically associated with rhyolite and biotite-muscovite granite, the so-called "tin granites," and that this association is so well marked on a worldwide scale that there seems little likelihood of finding significant tin in other geologic environments. Inasmuch as such rocks are characteristic of the craton, it is obvious that exploration for new-deposit resources of tin in the northeast quadrant should focus on the craton rather than on the accreted terranes. In addition to the tin associated with base metals at the Sullivan mine, the main areas of known tin mineralization are in (1) greisen-like deposits on the Seward Peninsula, Alaska, (2) a belt containing sporadic placer deposits across central Alaska (not shown on map), (3) abundant but small veins and encrustations in rhyolitic rocks in New Mexico and in central Mexico, (4) veins in granitoid and metamorphic rocks in the southern Sierra Nevada batholith, California (Sainsbury, 1969; Cobb, 1960), and (5) small vein, skarn, and greisen deposits in the McQuentin and Cassiar districts of Yukon and British Columbia (not shown on map). As noted by Sainsbury and Reed (1973) the geology of vein tin deposits is well understood, but the genesis of tin deposits and of "tin granite" remains a field for speculation and debate.

SILVER

Silver deposits fall into two broad categories: (1) deposits in which silver is a by-product or co-product produced with other metals, and (2) deposits in which silver is the major constituent. Heyl and others (1973) observed that most of the silver produced results from by-product or co-product production, and they listed nine types of deposits having such production. Chief among these are various types of base-metal deposits. On this map only those deposits in which silver is the major constituent are shown. Essentially, this includes silver-vein and replacement-type deposits. The distribution of silver deposits is thus restricted on this map, and does not reflect the distribution of all silver-bearing deposits.

The vein and replacement deposits occur mainly in areas underlain by continental crust or the craton, but also in some areas in Canada and western United States that are underlain by accreted island-arc terranes. No silver deposits are present in oceanic crust terranes except deposits in which gold is the principal metal. The great "bonanza"-type vein deposits such as Comstock and Tonopah, Nev. in the western United States are in postaccretionary volcanic rocks. At Comstock these host rocks overlie an accreted island-arc terrane, whereas at Tonopah the host rocks overlie continental crust of the craton. Most of the silver deposits that are in postaccretionary volcanic rocks in Mexico are underlain by either craton or accreted continental crust. The giant Coeur d' Alene district deposits near lat 47° N. long 116° W. are in Precambrian cratonal rocks.

In view of the exceedingly broad distribution of silver-bearing deposits, it is difficult to speculate on the source of the metal. Silver evidently can form in a large variety of tectonic environments. As reported by Heyl and others (1973) citing Degens and Ross (1969), seafloor muds of the Red Sea contain lead, zinc, iron sulfides, and some silver in lenticular basins. These metals are being deposited by heated brines rising through the seafloor in the central part of the Red Sea. In the Salton Sea area of southern California brines tapped from a deep drill hole

MINERAL INVESTIGATIONS
RESOURCE MAP MR-95

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MAP 1
INFERRED FAVORABLE AREAS FOR GOLD AND TUNGSTEN DEPOSITS AND OIL AND GAS FIELDS

EXPLANATION

DEPOSIT TYPE

[Where deposit types overlap, color of smaller deposit type is shown. Boundary of larger deposit type is dotted through smaller deposit type]

- ■ **Gold**—Vein
- ■ **Gold**—Disseminated
- ■ **Tungsten**
- ■ **Oil**
- ▨ **Gas**

TERRANE TYPE

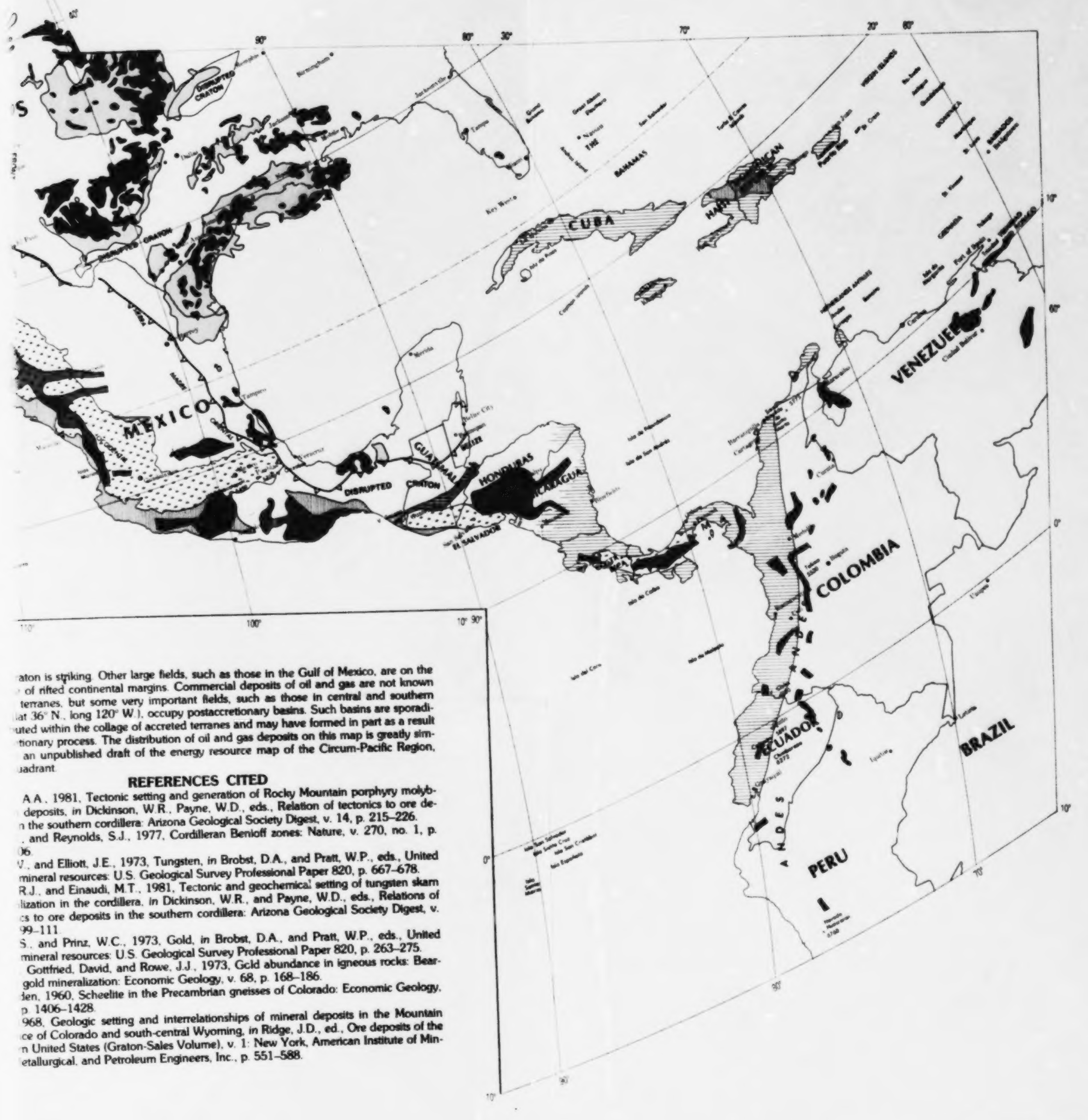
- ☐ **Postaccretionary sedimentary rocks**
- ▨ **Postaccretionary volcanic rocks**
- ▤ **Accreted oceanic crust**
- ▥ **Accreted island-arc crust**
- ☐ **Accreted continental crust and craton** (miogeoclinal and platform rocks)
- ▨ **Precambrian greenstone (shield)**
- ▨ **Batholithic rocks**

Contact—Between terrane types; approximately located

Boundary of deposit type—Dotted where inferred

Major frontal zone or fault zone—Dotted where inferred

East edge of disrupted craton—Sawteeth point away from craton



aton is striking. Other large fields, such as those in the Gulf of Mexico, are on the
of rifted continental margins. Commercial deposits of oil and gas are not known
terranes, but some very important fields, such as those in central and southern
lat 36° N., long 120° W.), occupy postaccretionary basins. Such basins are sporadi-
uted within the collage of accreted terranes and may have formed in part as a result
tionary process. The distribution of oil and gas deposits on this map is greatly sim-
an unpublished draft of the energy resource map of the Circum-Pacific Region,
uadrant.

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MERCURY

Mercury deposits in the northeast quadrant of the Circum-Pacific are almost completely restricted to accreted oceanic or island-arc terranes, or to postaccretionary rocks overlying such terranes. A few small deposits in Mexico, Alaska, and the western United States are in continental crust which in Mexico is thought to be accreted and not part of the craton. Mercury deposits are commonly found in tectonically active areas that have had Tertiary or Quaternary thermal activity indicated by volcanic rocks and hot springs.

Several types of mercury deposits are represented (but not differentiated) on the map. The largest producing area is in the Coast Ranges of California (lat 39° N., long 122° W.) where at least half the deposits are of the silica-carbonate type (Davis and Bailey, 1966) associated with serpentine. Deposits in western Canada are also mainly silica-carbonate type. Other principal deposit types are opalite, associated with Cenozoic volcanic rocks and common in parts of the Basin-Range region of the western United States, and veins in fault and shear zones cutting diverse types of rocks. All mercury deposits in the cordillera are geologically young; probably none are older than the late Oligocene. Deposits are less abundant in western Canada and Alaska than in the western United States, and are rare in Central America and northwestern South America.

A large area of small but productive mercury deposits lies outside lat 40° N. and east of long 120° W. The mercury occurs in a wide variety of rocks and in different types of deposits, but is primarily associated with silicic and intermediate volcanic rocks of Tertiary age. Most mercury deposits are located west of the $^{87}Sr/^{86}Sr = 0.706$ (craton boundary) line (Kistler, 1983) in accreted terranes, and most deposits show a marked alignment along northwest and northeast trends, indicating probable distributional control by fracture systems. Most deposits in Canada are postaccretionary and related to late movement on major faults, probably with accompanying epithermal or geothermal activity.

Although mercury deposits in the northeast quadrant are decidedly hosted in accreted oceanic or island-arc crust, the same relation is not found in other parts of the world. Bailey and others (1973) point out that, based on world-wide relations, almost any kind of rock may be the host, and they make a strong case relating mercury deposits to post-Jurassic subduction zones. They indicate that deposits are localized where oceanic crust has been subducted and speculate that mercury originally contained in subducted trench sediments, or in the subducted oceanic crust, "* * * was distilled out of the downward plunging plate and emplaced at a higher cooler level along or above the subduction zone." White (1967) had earlier proposed that eugeosynclinal sedimentary rocks might be the source of the mercury in some deposits in California. It seems fairly clear that the types of rock from which mercury can be readily leached or distilled in sufficient quantities to yield an ore deposit are of oceanic and not continental affiliation, whatever the type of terrane the mercury deposit is in.

URANIUM

Although uranium is commonly present in accreted terranes as well as in the craton, nearly all known deposits having commercial value are in platform and shield segments of the craton. More than 90 percent of Canadian deposits are in the western and southern parts of the Precambrian shield (Lang, 1952). These uranium deposits are primarily epigenetic vein-like deposits, which according to Ruzicka (1971), were initially formed mainly as uraninite (pitchblende) deposits during several mineralizing episodes between 2,600 and 1,000 Ma. Lang (1952) reports that basic rocks including amphibolite, basalt, and diabase dikes are the favorable host rocks for many uranium deposits, but believes the source of the uranium was "acid" magmas. Ruzicka (1971) concurs with this belief but adds that argillaceous sediments might also be a source.

Most of the vein deposits in the Precambrian shield of central Canada are localized along faults, shear zones, fracture systems, and igneous contacts (Lang, 1952); and Lang (1970), observing the dominance of northeast trends, postulates a series of northeast-trending lineaments, some 1,500 km long. A number of these postulated northeast-trending lineaments are within and follow the trend of greenstone belts.

In the western United States most uranium deposits of commercial value are epigenetic sedimentary deposits hosted by lenticular sandstone beds that range in age from the middle Paleozoic to the Pliocene (Finch, 1967; Young, 1978). The major host sandstones are of Triassic and Jurassic age. Most deposits are tabular layers that nearly parallel bedding (Finch, 1967). The host sandstones are thought to have formed mainly in continental environments such as successor basins, shallow depressions, intermontane basins, and coastal plains. Closely related to these peneconcordant epigenetic deposits are discordant "roll" and vein deposits that represent uranium derived from host sandstones and redistributed, mainly by oxygenated ground waters.

Uranium deposits in the western United States show a wide variation in isotopic ages. Data presented by Finch (1967) for 12 Colorado Plateau deposits show lead ages ranging from about 295 to 54 Ma. Rosenburg and Hooper (1982) report fission-track ages of about 6.7 Ma for redistributed sandstone-hosted uranium ore in the Grants mineral belt, New Mexico (lat 35° N., long 107° W.), and ages as young as 11,000–150,000 years are reported for some unoxidized uranium minerals in Wyoming north of lat 40° N. (Finch, 1967).

Of the numerous hypotheses that have been proposed for the origin of the sandstone-hosted uranium, it appears that Gruner's (1956) thesis of multiple migration-accretion, endorsed by Garrels (1957) and Finch (1967), best fits the widespread distribution of uranium and the scarcity of igneous rocks that characterize the epigenetic uranium deposits. This hypothesis holds that the source of uranium was the large volume of Precambrian rocks that were eroded in post-Pennsylvanian time, which could have provided at least 400 million tons of uranium. Gruner (1956) believes that given an interior basin environment, arid or semiarid conditions, and no access to the sea, this uranium could have been leached by Ca, Mg, or Na bicarbonates, and carried long distances in CO_2-rich groundwaters to sites where reducing conditions were met. Concentration of large deposits of uranium could result, according to Gruner, from several stages of oxidation-solution-migration-accretion.

The abundance of uranium and the similarity in age and lithology of Precambrian host rocks in the Canadian shield and the Rocky Mountain front range noted by Nash and others (1981) suggest the continuation of similar, probably uranium-rich Precambrian terranes beneath the western United States and seems to strongly support Gruner's thesis that the primary source of uranium is Precambrian rocks. Moreover, the mechanism they propose for its leaching, transport, and deposition explains convincingly the extremely broad distribution of sandstone-hosted deposits as well as the wide variation in their ages.

LEAD AND ZINC

Four main types of lead-zinc deposits are shown on the map. One is sediment-hosted exhalative massive sulfides, of which the Sullivan deposit in southern British Columbia, near lat 50° N., long 116° W., is perhaps the best known North American example. A second type is the mainly carbonate-hosted deposits such as in the western United States at Metaline, Wash., Tintic, Utah, and Darwin, Calif. Vein deposits typified by those of the Coeur d'Alene district of Idaho (lat 47° N., long 116° W.), and replacement (skarn, manto, chimney) deposits of the Sierra Madre Oriental in Mexico constitute a third major type. Volcanogenic massive sulfide deposits, mainly in the Canadian shield, that have yielded zinc and lead as the principal metals represent a fourth type. Only the first two types of lead-zinc deposits are discussed in this section.

SEDIMENT-HOSTED LEAD-ZINC DEPOSITS

Most of the known sediment-hosted (exhalative) massive sulfide lead-zinc deposits in the North America Cordillera are in British Columbia, the Northwest Territories, Yukon, and Alaska. Others occur in the vicinity of lats 43° and 44° N., and long 115° W. in the United States, but none have been identified south of the Snake River Plain (about lat 42°N.). The sediment-hosted massive sulfide deposits are restricted to the craton in Canada, but the deposits near long 115° W. in the United States are in allochthonous accreted sedimentary rocks. The Sullivan ore body, described by Hamilton and others (1983), is close to the craton boundary in siliceous rocks of Middle Proterozoic age. MacIntyre (1983) describes similar deposits in the Gataga district of northeastern British Columbia (not shown on map) as being hosted in lower Paleozoic deep-marine clastic sedimentary rocks that accumulated in structurally controlled basins and troughs located along the west margin of the North American craton from Cambrian to Late Devonian time.

According to an empirical model developed by Large (1983), the typical host environment for this deposit type is an epicratonic basin bounded by high-angle faults on one or both sides. Subsidence of the basin was controlled by faulting, and the mineral deposits are commonly close to these fault zones. First, second, and third order basins are recognized by Large (1983). The third order basins are smallest, measuring only a few hundred meters to a few kilometers in lateral extent, and are the morphological traps in which the stratiform sulfides accumulated. Many of the deposits contain abundant barite and chert as well as the sulfide ore minerals, and most contain significant amounts of silver. The deposits formed synchronously with their enclosing sediments at the time of basin sedimentation and result probably from hydrothermal fluids circulating in a convection cell and issuing as metal-laden brines from tectonically controlled discharge vents on the seafloor.

Inasmuch as the exhalative massive-sulfide deposits formed syngenetically with sedimentary rocks ranging in age from Middle Proterozoic to Carboniferous, they predate any recognized accretionary (compressional) episode in the western cordillera. Their morphology and depositional environment suggest formation in an extensional tectonic regime punctuated by episodes of rifting, a condition that Hutchinson (1980) noted was characteristic of Middle Proterozoic, and which may have persisted until the middle Paleozoic.

CARBONATE-HOSTED LEAD-ZINC DEPOSITS

Carbonate-hosted lead-zinc deposits include stratabound deposits of epigenetic origin, replacement deposits, and contact metasomatic deposits, in the terminology of Morris and others (1973). All replacement deposits are veins or veinlike. The stratabound deposits of presumed epigenetic origin are restricted to one or more (commonly carbonate) stratigraphic entities with no apparent igneous associations, whereas the replacement deposits, though in many respects similar, are commonly associated with intrusive rocks.

Carbonate-hosted deposits are restricted to miogeoclinal and platform rocks of the craton. They commonly occur in brecciated dolomite host rock in a zone of rapid lithological facies changes, such as between a sedimentary basin edge or a reef front and the tectonically stable platform. Their distribution from northern Alaska southward throughout the cordillera to Mexico and Guatemala reflects this relation. A notable exception is the Leadville district, Colorado (lat 39° N., long 106° W.).

Other important deposits and districts located east of the cordillera (not shown on the map) include Pine Point and Polaris, Northwest Territories; Newfoundland Zinc; and the Viburnum Trend and Old Lead Belt districts, Missouri.

As observed by Sangster (1984), no consensus exists on genetic models for carbonate-hosted lead-zinc deposits, or on ore controls and guides. However, Sangster states that one or more of the following features are commonly associated with these deposits: (1) secondary breccia in dolomite, cemented by white sparry dolomite, (2) unconformities within carbonate sequence (ore horizon will be below unconformities), (3) reefs, (4) carbonate-shale and limestone-dolomite facies changes, (5) basement high(s), (6) open spaces of any type within carbonate sequences, especially those formed by karstification as evidenced by brecciation, thinning of carbonate strata, and local increase in concentration of insoluble residue materials.

VOLCANOGENIC MASSIVE-SULFIDE DEPOSITS INCLUDING COPPER, LEAD, AND ZINC

Massive-sulfide deposits with volcanogenic associations are known from Alaska to Mexico. Those deposits of Phanerozoic age are either exclusively in, or closely associated with, volcanic rocks of submarine origin or with related sedimentary rocks of submarine origin. Such deposits are restricted to accreted terranes composed of island-arc or oceanic crust. Massive-sulfide deposits in Precambrian rocks of the craton are in greenstone belts that probably are manifestations of similar pre-Phanerozoic accretionary continental growth. Inasmuch as it is now generally accepted that the massive-sulfide deposits formed syngenetically with their enclosing host rocks, these deposits in Precambrian rocks are of preaccretionary age, although some may have been modified by thermal events accompanying or following accretion.

Two major types of massive-sulfide deposits having markedly different lithologic affiliation and sulfide mineralogy are found in the accreted terranes. One type is typically found in silicic rocks of calc-alkaline affinity in island-arc terranes; the other type is associated with tholeiitic or calc-alkaline, predominantly mafic volcanic rocks of deeper ocean or marginal-basin origin. The deposits in island-arc terranes are by far the most common. They are typically hosted by submarine flows, tuffs, and breccias of silicic to intermediate composition or by sedimentary rocks closely associated with mafic to silicic volcanic rocks. Major sulfide minerals are pyrite, chalcopyrite, sphalerite, and, less commonly, galena, pyrrhotite, and magnetite. Silver is present in tetrahedrite or tennantite, and gold occurs in its native form. The proportions of the sulfide minerals may differ widely from one district to another or even from one deposit to another, and one or more mineral may be absent in some deposits. Quartz as a gangue mineral is ubiquitous, and sulfate minerals such as barite and anhydrite are locally common. A feeder stockwork or pipe consisting of a network of sulfide veinlets in chloritized host rock is characteristic of many (proximal) deposits (Large, 1977), but other sulfide bodies believed to have formed in seafloor basins (distal) have no such stockwork.

There is now general agreement that the massive-sulfide deposits in island-arc terranes formed at fracture controlled submarine volcanic centers during late stages of volcanic activity above a subducting slab. Such deposits form in an extensional tectonic environment where submarine fumaroles or hot springs debouched metal-laden brines on or very closely beneath the seafloor (Sillitoe, 1973). Intrusion and extrusion of igneous melts, especially of felsic composition, are commonly controlled by the same fracture system. The common position of the sulfide bodies at or near the top of a differentiated volcanic pile indicates that the metal-rich brines could well be a final product of magma differentiation; but a more probable source may have been metals leached from volcanic rocks lower in the pile by a hydrothermal convection system that dispelled its flow in or near the central volcanic conduit.

Deposits genetically related to oceanic basalt and found in accreted oceanic-crust terranes, commonly referred to as Cyprus-type deposits, are not abundant in the northeast quadrant of the Circum-Pacific, but a few such deposits of diverse Phanerozoic ages are known in the western United States, western Canada, and southern Alaska. They are typically pyritic bodies with chalcopyrite the principal ore mineral, sphalerite in relatively minor amounts, and minor quantities of cobalt, lead, gold, and silver. They are believed to have formed at ocean-ridge or back-arc spreading centers from mantle-derived magma by processes much like the ones that formed the deposits hosted in the more silicic island-arc rocks.

Although most volcanogenic massive-sulfide deposits have yielded copper as their principal base metal, many deposits of this type also contain substantial amounts of zinc and lead as well as precious metals. In the Canadian shield some of the polymetallic massive-sulfide deposits have been worked mainly for lead and zinc, and these areas are shown on map 2.

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MAP 2
INFERRED FAVORABLE AREAS FOR MERCURY, URANIUM, LEAD-ZINC, AND VOLCANOGENIC MASSIVE SULFIDE DEPOSITS

EXPLANATION

DEPOSIT TYPE

[Where deposit types overlap, color of smaller deposit type is shown. Boundary of larger deposit type is dotted through smaller deposit type]

- ■ **Mercury**
- ■ **Uranium**
- ■ **Lead-Zinc**—Sediment hosted
- ■ **Lead-Zinc**—Carbonate hosted
- ▨ **Lead-Zinc**—Vein and stockwork
- ■ **Lead-Zinc**—Volcanogenic massive sulfide
- ▨ **Copper**—Volcanogenic massive sulfide

TERRANE TYPE

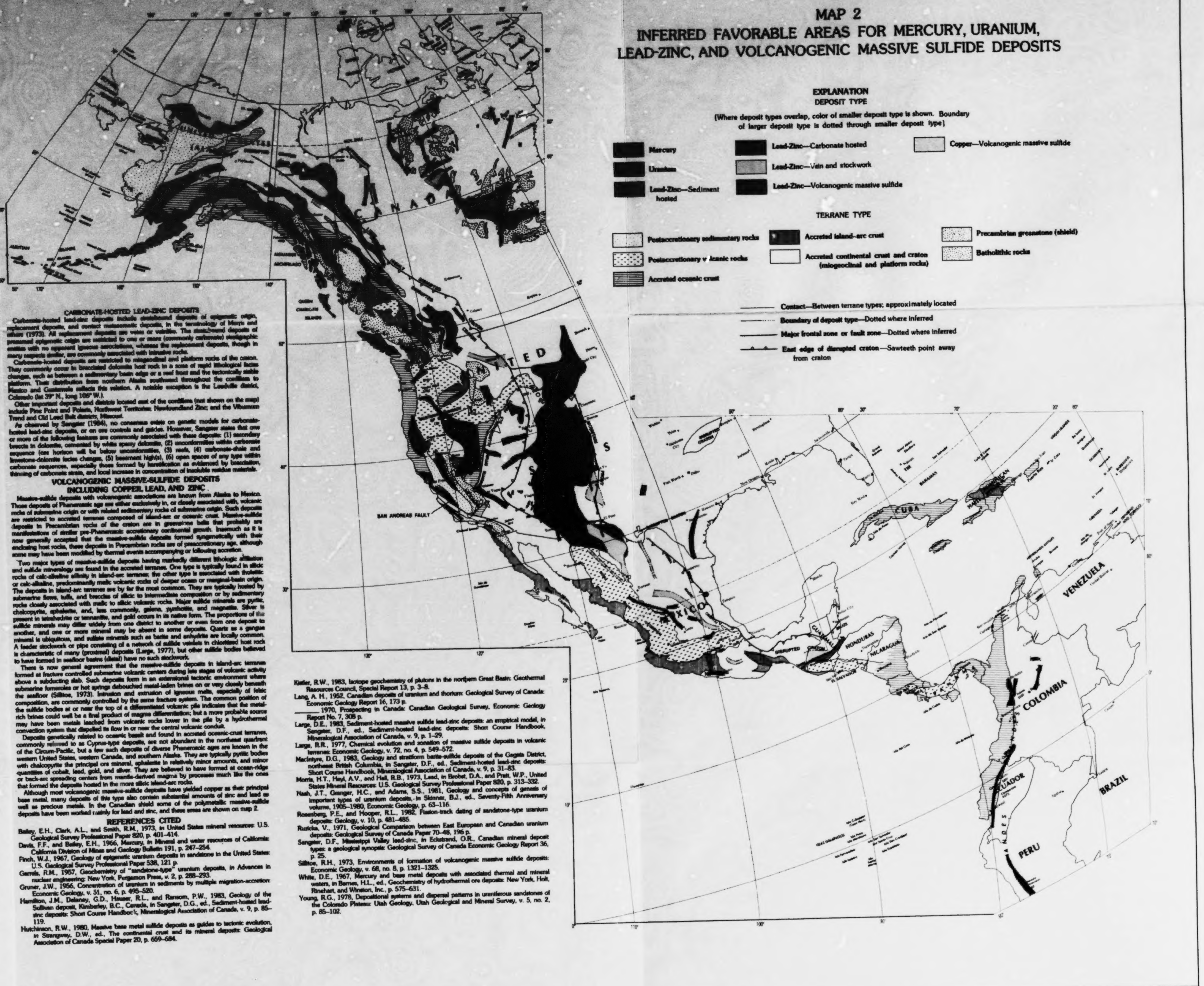
- ☐ **Postaccretionary sedimentary rocks**
- ▨ **Postaccretionary volcanic rocks**
- ▤ **Accreted oceanic crust**
- ▥ **Accreted island-arc crust**
- ☐ **Accreted continental crust and craton** (miogeoclinal and platform rocks)
- ▨ **Precambrian greenstone (shield)**
- ▨ **Batholithic rocks**

Contact—Between terrane types; approximately located

Boundary of deposit type—Dotted where inferred

Major frontal zone or fault zone—Dotted where inferred

East edge of disrupted craton—Sawteeth point away from craton



MAP 3
INFERRED FAVORABLE AREAS FOR MANGANESE, FLUORSPAR, IRON, AND MOLYBDENUM DEPOSITS

EXPLANATION

DEPOSIT TYPE

[Where deposit types overlap, color of smaller deposit type is shown. Boundary of larger deposit type is dotted through smaller deposit type]

- ▨ **Manganese**—Volcanogene
- ■ **Manganese**—Sedimentary
- ■ **Manganese**—Vein (hypogene)
- ■ **Fluorspar**—Vein
- ☐ **Iron**—Skarns (contact metosomatic)
- ■ **Iron**—Sedimentary
- ☐ **Molybdenum**—Porphyry

TERRANE TYPE

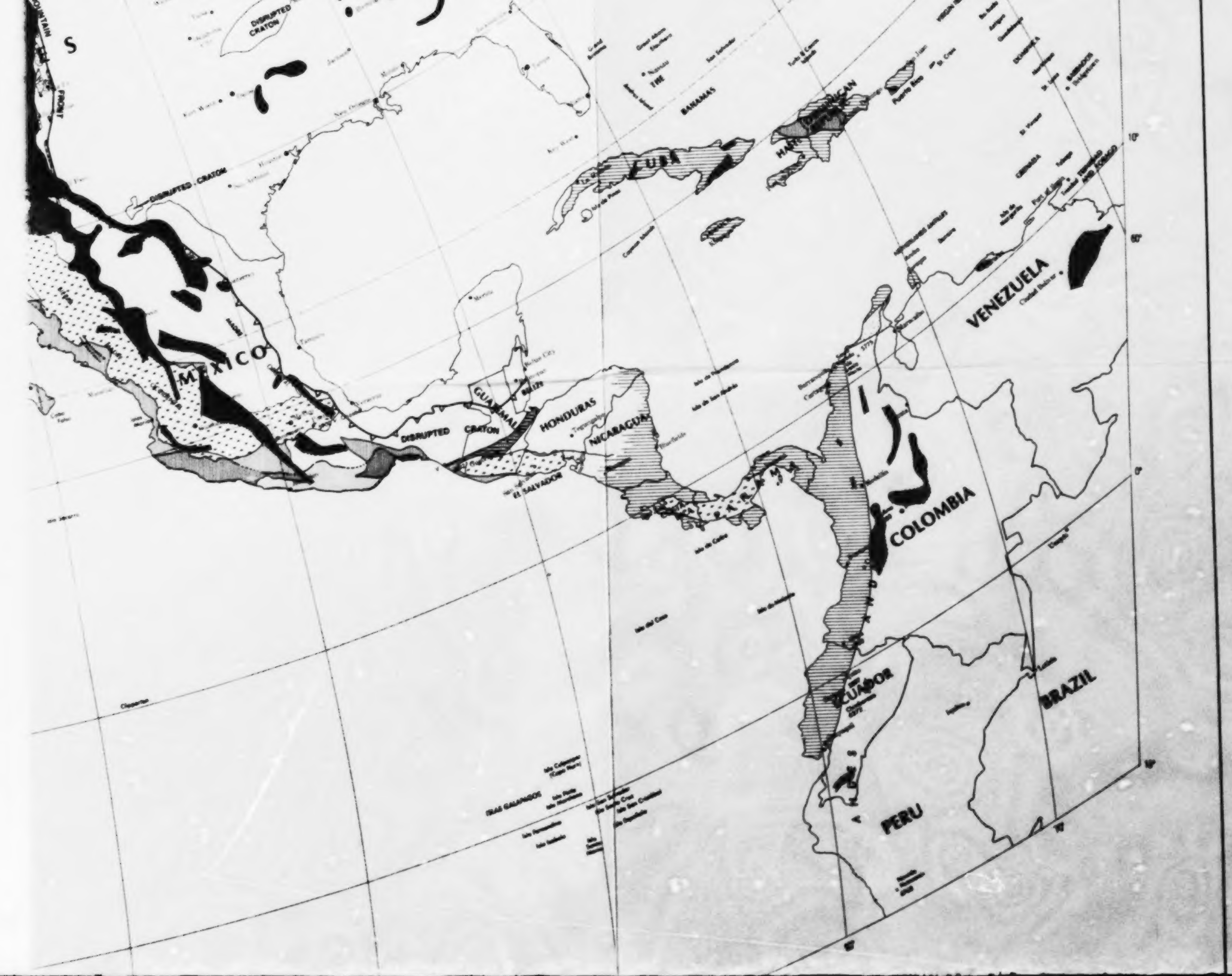
- ☐ **Postaccretionary sedimentary rocks**
- ▨ **Postaccretionary volcanic rocks**
- ▤ **Accreted oceanic crust**
- ▥ **Accreted island-arc crust**
- ☐ **Accreted continental crust and craton** (miogeoclinal and platform rocks)
- ▨ **Precambrian greenstone (shield)**
- ▨ **Batholithic rocks**

Contact—Between terrane types; approximately located

Boundary of deposit type—Dotted where inferred

Major frontal zone or fault zone—Dotted where inferred

East edge of disrupted craton—Sawteeth point away from craton



PORPHYRY COPPER AND PORPHYRY COPPER-MOLYBDENUM DEPOSITS

The porphyry copper deposits, including those containing significant gold, and the porphyry copper-molybdenum deposits, are variants of a single deposit type and are grouped together on map 4. They are generally associated with hypabyssal calc-alkalic intrusions ranging in composition from quartz monzonite to diorite (Hollister, 1978).

It is evident from their distribution from north to south that while the porphyry-type deposits are not characteristic of any one type of terrane over the expanse of the northeast quadrant of the Circum-Pacific, they are nevertheless restricted to individual terrane types within specific large regions. Porphyry deposits in Alaska are in two belts, one in accreted island-arc terrane and the other in the craton, whereas the deposits in British Columbia are confined almost entirely to accreted island-arc terranes. The majority of porphyry-type deposits in the western United States and northern Mexico are in the craton; exceptions are deposits at Yerington, Nev. (lat 42° N., long 124° W.), and at Lights Creek, Calif. (lat 39° N., long 120° W.), which are in accreted island-arc terranes. Largely undeveloped porphyry-type deposits in southern Mexico are hosted in island-arc terrane, while those in Panama, Colombia, and Ecuador are in accreted oceanic crust terrane as far south as 4° S. latitude. Beyond that, to the south edge of the map at lat 10° S., several large porphyry copper-molybdenum deposits are in the continental margin magmatic arc of the craton. Although porphyry deposits hosted in each of the three major types of terranes have distinctive geologic features, it is apparent that physical and compositional features of the deposits show a common thread throughout the length of the cordillera, suggesting a similar genesis for the deposits and probably a common source for the metals.

The age of porphyry deposits within the western cordillera ranges from Triassic to the late Tertiary. The age range in the southwestern United States and northern Mexico is remarkably narrow (about 20 Ma), whereas deposits in central British Columbia show an overall range of about 163 Ma and a clustering within perhaps six rather distinct age groups (Christopher and Carter, 1976). The oldest porphyry copper deposits in the northeast quadrant of the Circum-Pacific (British Columbia) formed slightly more than 200 Ma, or about the time of the opening of the Atlantic Ocean, which may indicate a possible genetic relationship between plate movement and the formation of porphyry-type deposits. This time (~200 Ma) is slightly prior to accretion of the host terranes in Early and Middle Jurassic time, therefore, the oldest British Columbia porphyries are preaccretionary in age.

At least 90 percent of the porphyry deposits in the southwestern United States and northern Mexico, and a high percentage of such deposits in British Columbia, the Caribbean, and in the western United States were formed during the Laramide orogeny, a relatively short span of time lasting from about 80 to 40 Ma (Coney, 1976). Age differences within the Laramide interval probably result from migration of a magmatic arc above a shallow, gently-dipping subducting slab.

The marked tendency for the porphyry-type deposits to occur in elongate belts inboard from present or former subducting plate boundaries indicates that these deposits are genetically related to the subduction process. No so easily explained is the tendency for some porphyry-type deposits to occur in clusters in the southwestern United States and central British Columbia, or the occurrence of such isolated very large deposits as those at Butte, Bingham, and Ely in the western United States. The answer to this question may be control by large, intersecting fracture systems penetrating the entire thickness of the crust. Also, some porphyry deposits may be buried by young cover rocks, in which case clustering might be only an apparent phenomenon.

Sillitoe (1972) has presented a cogent argument that porphyry deposits constitute a normal facet of calc-alkaline magmatism, and that the components of calc-alkaline igneous rocks and porphyry deposits are generated by partial melting of oceanic crustal rocks in underlying subduction zones at the elongate compressive juncture between lithospheric plates. He argues further that the only source of metals available to all porphyry copper deposits, taking into consideration the thin crust and almost total absence of sialic crust beneath some copper provinces (such as the Solomon Islands), would seem to be the upper mantle, the probable ultimate source of metals in virtually all mineral deposits. Burnham (1981) points out that during metamorphism of oceanic basalt containing an average of 77 parts per million (ppm) copper and 1,000 ppm FeS during subduction, nearly all the copper would combine with the FeS to form a pyrrhotite solid solution that would dissolve and provide an ample source of copper for porphyry deposits upon melting of the amphibolite. Burnham (1981) concludes "it is unnecessary to call upon abnormally copper-rich rocks, such as the metalliferous sediments of the Nazca plate (or copper-rich Precambrian basement rocks), for the sources of ore-bearing magmas."

This argument is most convincing for the numerous deposits that lie inboard a reasonable distance (150–250 km) from present or former trenches of subduction zones. However, a rational explanation for distant relatively isolated deposits hundreds of kilometers from such trenches is more elusive. Coney and Reynolds (1977) tracked the systematic variation in the radiometric ages of Cretaceous and Tertiary igneous rocks, and concluded that the dip of the Benioff zone (subducting slab) flattened progressively beneath southwestern North America during the interval beneath 130–110 Ma and about 55–40 Ma. The decrease in dip is believed due to a high rate of convergence—the higher the rate, the lower the angle of dip. If this analysis is correct, the copper and other metals in the great porphyry deposits of Butte, Bingham, and Ely could have come from partial melting of shallow-dipping relatively fast-moving subducting slabs. Further support for this argument is that similarities in general geochemistry of intrusive rocks associated with porphyry copper deposits and style of porphyry copper mineralization in continental terranes, compared to that in island-arc terranes, suggest that the magmas in both types of terranes were probably largely derived beneath the crust, and that continental contamination contributed insignificantly to the magma or metals (Mitchell and Garson, 1981).

One further point worth noting is that, while most deposits of the porphyry type appear in general to be spatially related to a subduction zone and hence to a compressional tectonic regime, it is also evident that a high percentage of porphyry deposits are localized at or near the intersection of important fracture systems, one system commonly being strike slip, and the other extensionial dip slip (Hollister, 1978; Titley, 1982). This is further borne out by the presence of abundant dikes closely associated with porphyry copper deposits, which clearly indicates an extensional environment at the time of intrusion and mineralization. The favored structural environment in which many porphyry systems were emplaced would thus appear to be tensional, at least at the level of emplacement.

TIN

Deposits of tin in the northeast quadrant of the Circum-Pacific are sparse, widely scattered, and small. The few deposits that have produced tin are widely separated localities from the Seward Peninsula in Alaska to central Mexico. Some tin has been produced as a by-product in the production of other metals, mainly from the Sullivan lead-zinc mine in southern Canada (lat 50° N.). All the deposits that have produced tin are in the craton, but unproductive occurrences of tin are present in accreted terranes as well as in the craton.

Sainsbury and Reed (1973) observe that tin deposits are typically associated with rhyolite and biotite-muscovite granite, the so-called "tin granites," and that this association is so well marked on a worldwide scale that there seems little likelihood of finding significant tin in other geologic environments. Inasmuch as such rocks are characteristic of the craton, it is obvious that exploration for new-deposit resources of tin in the northeast quadrant should focus on the craton rather than on the accreted terranes. In addition to the tin associated with base metals at the Sullivan mine, the main areas of known tin mineralization are in (1) greisen-like deposits on the Seward Peninsula, Alaska, (2) a belt containing sporadic placer deposits across central Alaska (not shown on map), (3) abundant but small veins and encrustations in rhyolitic rocks in New Mexico and in central Mexico, (4) veins in granitoid and metamorphic rocks in the southern Sierra Nevada batholith, California (Sainsbury, 1969; Cobb, 1960), and (5) small vein, skarn, and greisen deposits in the McQuesten and Cassiar districts of Yukon and British Columbia (not shown on map). As noted by Sainsbury and Reed (1973) the geology of vein tin deposits is well understood, but the genesis of tin deposits and of "tin granite" remains a field for speculation and debate.

SILVER

Silver deposits fall into two broad categories: (1) deposits in which silver is a by-product or co-product produced with other metals, and (2) deposits in which silver is the major constituent. Heyl and others (1973) observed that most of the silver produced results from by-product or co-product production, and they listed nine types of deposits having such production. Chief among these are various types of base-metal deposits. On this map only those deposits in which silver is the major constituent are shown. Essentially, this includes silver-vein and replacement-type deposits. The distribution of silver deposits is thus restricted on this map, and does not reflect the distribution of all silver-bearing deposits.

The vein and replacement deposits occur mainly in areas underlain by continental crust or the craton, but also in some areas in Canada and western United States that are underlain by accreted island-arc terranes. No silver deposits are present in oceanic crust terranes except deposits in which gold is the principal metal. The great "bonanza"-type vein deposits such as Comstock and Tonopah, Nev. in the western United States are in postaccretionary volcanic rocks. At Comstock these host rocks overlie an accreted island-arc terrane, whereas at Tonopah the host rocks overlie continental crust of the craton. Most of the silver deposits that are in postaccretionary volcanic rocks in Mexico are underlain by either craton or accreted continental crust. The great Coeur d'Alene district deposits near lat 47° N. long 116° W. are in Precambrian continental rocks.

In view of the exceedingly broad distribution of silver-bearing deposits, it is difficult to speculate on the source of the metal. Silver evidently can form in a large variety of tectonic environments. As reported by Heyl and others (1973) citing Degens and Ross (1969), seafloor muds [illegible] tholeiitic volcanoes (Hekinian and others 1980). The source of the silver and other metals in the Red Sea and Salton Sea may have been a deep magmatic source, as believed by White and others (1963), or it may have been derived from leaching of evaporite beds or deltaic sediments (Craig, 1969). The uncertainty illustrates the high degree of speculation in identifying the primary source of metals in nearly any type of deposit, even those that can be observed forming today. Silver in particular, because of the extremely scattered distribution of its deposits, may have come from multiple sources.

BARITE

Deposits of commercial barite have been divided into three main types by Brobst (1973): vein and cavity filling, residual, and bedded. Only the bedded and vein-type deposits are significant in the northeast quadrant of the Circum-Pacific and they are not differentiated on the map. Bedded deposits, the most important type commercially, occur in rather well-defined arcuate belts in the cordillera from eastern Alaska southward to northern Mexico, and in Colombia, South America. No bedded deposits have been identified in the published literature from central and southern Mexico or Central America, although Reyna (1956) mentions that small barite deposits are present in nearly all parts of Mexico. Some of these may be the bedded type. Large bedded deposits are also present in the Ouachita Mountains of the south-central United States.

Most bedded barite deposits in western North America are Cambrian to Mississippian in age. However, some deposits in northern Mexico are as young as Pennsylvanian, and the Colombian deposits are in sedimentary rocks of Cretaceous age. In British Columbia and the Yukon, stratiform barite deposits hosted by cratonal Devonian and Mississippian clastic rocks and locally associated with sedimentary exhalative lead, zinc, silver, and barium deposits constitute the largest known barite resource in the cordillera. Stratabound barite-fluorite deposits in Devonian shelf carbonate rocks of the northern Canadian Rockies also constitute a significant resource (Dawson, 1983). In the western conterminous United States, large deposits of bedded barite are interlayered with radiolarian chert and shaly mudstone of Ordovician and Devonian age. The large deposits in part of the Roberts Mountains allochthon (Shawe and others 1969) have been displaced more than 80 km eastward from their depositional site. Therefore, although they reside inland from the craton boundary, they formed in accreted oceanic crust terrane. Devonian and Mississippian deposits in California are in accreted island-arc terranes. Large bedded deposits in the Ouachita Mountains are chiefly in Devonian and Mississippian dark shaley rocks (Brobst, 1973), and deposits in northern Mexico are in accreted eugeoclinal rocks ranging in age from Devonian to Early Pennsylvanian (Poole and others 1983). Smaller bedded deposits in Colombia are in Mesozoic miogeoclinal sedimentary rocks.

The association of bedded barite with turbidite clastic rocks, dark shale, and chert of deep-water origin and chiefly of middle Paleozoic age is striking. The overall map distribution indicates that in areas such as British Columbia, deposition occurred slightly inside the continental margin in elongated fault-bounded basins or grabens. The barite in base-metal districts within this region is genetically related to exhalative base-metal sulfide deposits whose source was a system of submarine hydrothermal events (Dawson and Orchard, 1982). In the western and southern United States and in Mexico, barite is found primarily in allochthonous sedimentary rocks whose protoliths perhaps originated in back-arc basins outside the continental margin. Recent seafloor investigations have proven that barite, together with other sulphate, silicate, oxide, and sulfide minerals is deposited from fault-controlled hydrothermal vents in the San Clemente fault zone near San Diego, Calif. (Lonsdale, 1979) and along the East Pacific Rise (not shown on map) (Hekinian and others 1980).

ANTIMONY

Antimony in the northeast quadrant of the Circum-Pacific occurs mainly as veins and irregular replacements in miogeoclinal sedimentary rocks and the granitic rocks that intrude them. Numerous productive vein deposits also occur in postaccretionary volcanic rocks that overlie miogeoclinal rocks. Fairly numerous but small deposits in Canada and in the western United States are in island-arc terranes. Two deposits, one in California and one in central British Columbia (not shown on map), are associated with mercury in accreted oceanic crust. The largest production has come from vein deposits in miogeoclinal rocks and postaccretionary volcanic rocks in Mexico, and from polymetallic vein deposits in Idaho (lat 45° N., long 117° W.) where antimony was a by-product in the production of base and precious metals (Miller, 1973). However, antimony is the sole metal produced from some epithermal vein deposits in Nevada (approx. lat 40° N., long 119°–116° W.) (Lawrence, 1963) and in Mexico (Reyna, 1956).

The distribution of productive antimony deposits is rather similar to deposits of tin and tungsten in that the great majority of deposits are within the craton but fairly close to its outer boundary, within the span of miogeoclinal rocks. A discontinuous belt of antimony deposits extends from southern Mexico northward to about lat 49° N. Only a few small deposits are known in British Columbia (not shown on map). Antimony deposits in Alaska, although numerous, are all small and of little economic value (not shown on map). In the western United States the antimony belt largely overlaps the areas of tungsten and tin deposits. In Mexico, antimony seems to have no spatial relation to tungsten but lies in a discrete belt east of the main belt of tin deposits.

The narrow linear belts of antimony deposits suggest spatial relation to a subduction zone. The spatial correlation between antimony and tungsten and the similar style in occurrence within and parallel to the craton suggests that the source of the antimony may have been from the same magma region as the tungsten, that is, from partial melting of a subducting slab. The antimony may have been [illegible] or less reactive with carbonate rocks than tungsten at the deeper crustal levels, and may have moved to higher levels to form the predominantly epithermal deposits.

PHOSPHATE

Deposits of phosphate of commercial or potentially commercial value include several types (Cathcart and Gulbrandsen, 1973), the most important of which is marine sedimentary phosphorite. [illegible]

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MAP 4
INFERRED FAVORABLE AREAS FOR COPPER, TIN, SILVER, BARITE, ANTIMONY, AND PHOSPHATE DEPOSITS

EXPLANATION

DEPOSIT TYPE

[Where deposit types overlap, color of smaller deposit type is shown. Boundary of larger deposit type is dotted through smaller deposit type]

- ■ **Copper**—Porphyry
- ■ **Tin**—Vein, greisen, skarn
- ■ **Silver**—Vein and replacement
- ■ **Barite**—Vein and bedded
- ☐ **Antimony**—Vein and replacement
- ■ **Phosphate**—Sedimentary

TERRANE TYPE

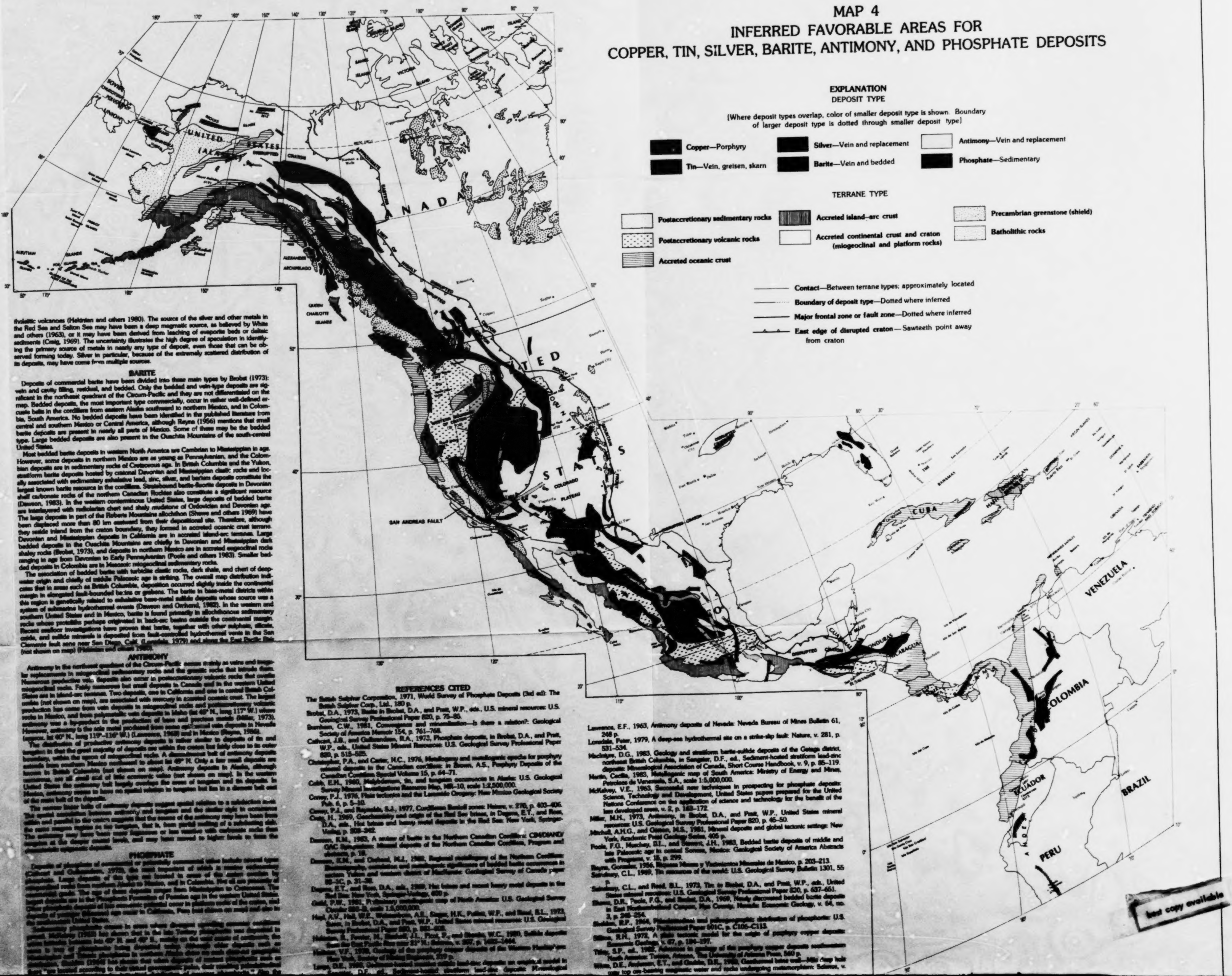
- ☐ **Postaccretionary sedimentary rocks**
- ▨ **Postaccretionary volcanic rocks**
- ▤ **Accreted oceanic crust**
- ▥ **Accreted island-arc crust**
- ☐ **Accreted continental crust and craton** (miogeoclinal and platform rocks)
- ▨ **Precambrian greenstone (shield)**
- ▨ **Batholithic rocks**

Contact—Between terrane types; approximately located

Boundary of deposit type—Dotted where inferred

Major frontal zone or fault zone—Dotted where inferred

East edge of disrupted craton—Sawteeth point away from craton



[illegible] and relative size of individual types of deposits at a scale of 1:20,000,000. The principal sources used in the compilation were the metallogenic maps of North America by Guild (1981) and Dawson (1984), supplemented by additional data from other sources. Only deposits that have a record of production or that have a demonstrated potential for producing a mineral product were considered in the analysis. The transparency for a particular type of deposit was superposed on a map of the same scale showing the accreted terranes and craton, and lines were drawn enclosing groups of deposits that are fairly closely spaced or that appear to be distributed along linear belts. On the maps, solid lines are used to indicate points of control by one or more deposits, and dotted lines indicate our projection between control points. Linear trends of some types of deposits, such as massive sulfides, are clearly restricted to, and controlled by, specific terranes or types of terranes. Linear trends of other types of deposits, such as porphyry copper, cross terrane and craton boundaries and appear to be controlled by other factors, such as megafracture systems and the position of subducting slabs during partial melting events. Whatever the geologic causes controlling the distribution of a deposit type, we wish to emphasize that the areas delineated as favorable by the dotted projections on the maps are based primarily on our interpretation of the distribution of known deposits, supplemented by generally well-known empirical observations that discrete types of deposits are favored by specific types of rock structures, or magmatic association. The results show that individual terranes are typically characterized by one or more specific deposit types or, in some cases, by no deposits. For example, certain accreted island-arc terranes are characterized by massive sulfide deposits, whereas other arc terranes may contain an abundance of skarn iron deposits, or perhaps gold quartz veins. The 1:20,000,000-scale maps on this sheet do not show individual terranes. Instead, all similar terrane types, such as island-arc terranes, are grouped together in order to form coherent cartographic units that can be readily recognized at the map scale.

The maps show that of the 25 types of deposits depicted 6 are characteristic of accreted oceanic or island-arc terranes and 11 are strongly characteristic of cratonal rocks. Eight deposit types are not confined to a particular terrane type over the length of the cordillera but may have a tendency to be restricted to one particular type of terrane within large regions. The grouping of the major types of accreted terranes (for example, oceanic and island arc) unfortunately obscures the relation of deposit types to specific tectonostratigraphic terranes as described above. Similarly, the spatial relation of many deposits to small plutons and important lineaments, whether in accreted terranes or the craton, could not be satisfactorily depicted at this map scale, although the east-northeast orientation of some mineral belts in the craton is a broad reflection of some of these features, particularly lineament control. The grouping of deposit types on the individual maps is for cartographic convenience only and has no genetic connotation. The text accompanying each map discusses distinctive features of the types of deposits and their distribution, gives pertinent information on the age of the deposits, and in most cases includes a brief discussion of the possible source or sources of the metals.

Except in Alaska, a striking feature of mineral belts in accreted terranes is their tendency to parallel the trend of host terranes or the trend of a particular host bed or zone within host terranes. Although mineral belts in the craton show a similar alignment, they also show a definite east-northeast trend in the western conterminous United States and in the Canadian shield. In the latter area, this trend clearly reflects the trend of the greenstone belts, with which the majority of deposits in the shield are associated. The east-northeast trend of mineral belts in the western United States may in part reflect concealed basement trends, but we believe this alignment reflects control by major extensional fracture systems that existed in a region at the time specific deposits were being formed.

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OTHER SOURCES OF INFORMATION AND ACKNOWLEDGMENTS

Unpublished map showing distribution of mineral deposits of Mexico provided by courtesy of Guillermo Salas of Consejo de Recursos Minerales, Mexico City.

Alaska Mineral Resource Assessment Program—USGS open-file maps of various Alaskan 1:250,000-scale quadrangles showing distribution of mineral deposits.

Detailed information on mineral deposits for California and Nevada in the files of authors, supplied mainly by USGS colleagues familiar with some of the recently discovered deposits.

Information on location and size of 70 mineral deposits in northern South America provided by Jose Corvalan of Chile.

Distribution of oil, gas, coal, and oil-shale deposits is greatly simplified from Circum-Pacific Northeast Quadrant Energy-Resource map.

These maps have been modified and improved substantially as a result of reviews by V.E. McKelvey, G.W. Moore, W.J. Nokleberg, M.G. Sherlock, and E.W. Tooker. It is a pleasure to express our thanks to these reviewers, and also to W.O. Addicott and J.A. Reinemund for their advice and encouragement during the course of the project.

[illegible] two types, vein-gold deposits and disseminated-gold deposits. Vein-type deposits of gold are more common than any other type of mineral deposit throughout the cordillera from western Alaska to Central America and northwestern South America. As illustrated on the map, areas favorable for these deposits show a pronounced tendency to occur in elongate belts, the vast majority of which are in accreted island-arc and oceanic-crust terranes and are oriented about parallel to the direction of terrane elongation. This elongation commonly is controlled by a favorable stratigraphic zone or an extensional structural zone. An example of elongation is the Mother Lode gold belt of California [illegible], which may, however, be a transpressional fault system formed within a compressional strike-slip system.

Vein-gold deposits in the craton are markedly less abundant than in the accreted terranes, although some very important bonanza-type deposits in postaccretionary volcanic rocks are underlain by cratonal terrane, as are some of the giant base-metal deposits, such as Bingham Canyon in Utah (lat 40° N., long 112° W.), from which gold has been recovered as a byproduct. Most of the large gold-producing areas of the Precambrian shield are in greenstone belts whose origin and mode of accretionary emplacement may have been similar to that of the accreted Phanerozoic island-arc and oceanic terranes.

Placer deposits are not shown separately on the map, but are commonly associated with the vein- rather than with the disseminated-gold deposits.

VEIN-GOLD DEPOSITS

Vein-gold deposits are almost entirely found in accreted island-arc and oceanic crust rather than in sialic crust of the craton, which suggests a genetic relation. It is well demonstrated (Tilling and others, 1973) that the geochemical abundance of gold in mafic plutonic and volcanic rocks is greater than in felsic and intermediate rocks. The possibility that gold was leached from mafic rocks by heat and fluids generated during magmatism and concentrated in vein deposits thus seems attractive. The important role of magmatism is indicated by the commonly close spatial relation of vein-gold deposits and intrusive rocks, and, in contrast, by the virtual absence of vein-gold deposits in accreted terranes that show little evidence of having undergone a significant thermal event, such as the terranes of the Franciscan assemblage of California.

Relatively sparse but large deposits of gold are found in Precambrian shield greenstones, and where found in younger (cratonic) rocks, could be derived from an underlying Precambrian greenstone source, or from a partly melted subducted slab of oceanic crust. The latter source seems more likely for gold in porphyry-copper deposits where the metals were probably all derived from subducting slab partial-melt source, as explained more fully in the text of map 4.

DISSEMINATED-GOLD DEPOSITS

Disseminated-gold deposits have become commercially important only in recent years. Particles of very fine grained gold (0.01–10 microns) characterize the ore. A prominent belt of these deposits in miogeoclinal rocks in central Nevada (lat 40° N., long 117° W.) is hosted in a variety of sedimentary and volcanic rocks ranging from Silurian to Miocene in age (Simons and Prinz, 1973). The deposits are mainly of Tertiary age and are believed to have been formed by hydrothermal replacement of the host rock. The source of the gold is not known. A recently discovered large disseminated deposit about 150 km north of San Francisco Bay, the McLaughlin deposit (near lat 39°N., long 122° W.), is in accreted oceanic crust, and it seems clearly to have been formed as a result of hot-spring activity that also produced a large amount of silica. The source of both gold and silica was most likely the accreted mafic and ultramafic host rocks.

TUNGSTEN

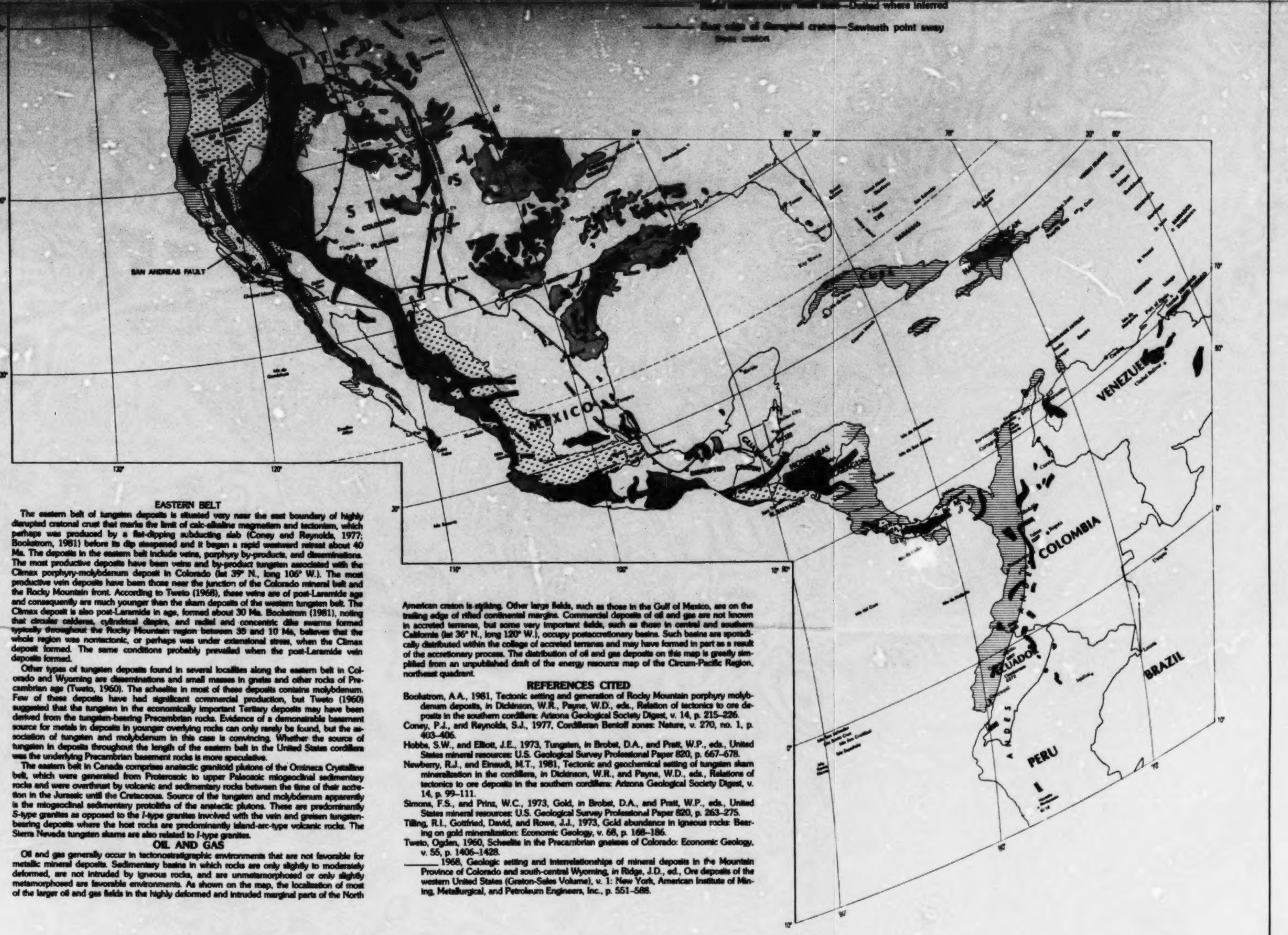
According to Hobbs and Elliott (1973), the major types of tungsten deposits are tactite (or skarn), hydrothermal veins, and stockworks and related tungsten-bearing porphyry molybdenum deposits. All these deposit types are present in the northeast quadrant of the Circum-Pacific from eastern Alaska and the northern Canadian cordillera to the northern part of Mexico, but they are not differentiated on map 1.

Most of the major production of tungsten is from skarn deposits. The deposits in western Canada are predominantly skarns that lie mainly just inside the craton boundary; however, several significant tungsten-bearing porphyry, vein, and greisen deposits occur within accreted terranes. Most of the Mexican deposits are similarly located. In the western conterminous United States, two distinct belts of productive deposits are recognized; (1) A rather broad western belt of mainly skarn-type deposits and subordinate veins extends approximately along the craton margin southward continuously from the Canadian skarns to northern Mexico. (2) A narrow eastern belt, broken near lat 36° N., long 107° W., and characterized mainly by vein deposits, extends generally south along the Rocky Mountain front from the vicinity of lat 45° N., long 111° W. to the Mexican border at about long 105° W.

It is evident from the distribution pattern that the vast majority of tungsten deposits are in the craton, and most of these are near the outer craton margin. However, several highly productive deposits in northwestern Nevada, southeast of lat 42° N., long 120° W., are in accreted island-arc terrane.

WESTERN BELT

Newberry and Einaudi (1981) point out that the tungsten skarns in the western cordillera occur in carbonate host rocks of Cambrian to Jurassic age in association with calc-alkalic intrusive rocks of Late Triassic to Late Cretaceous age. The skarns typically occur in miogeoclinal argillaceous limestone in the lowest exposed carbonate bed of a stratigraphic sequence. Thus, basal Cambrian limestones are host rocks in a number of important areas in western United States. Newberry and Einaudi (1981) have shown that tungsten skarns typically form at a temperature of 500–650 °C and a pressure of 2 pascals. They conclude that cordilleran tungsten skarns have formed in a relatively deep high pressure-temperature environment. They observe that, in a broad tectonic framework, depth to the lowest carbonate horizon in the crust is equivalent in many cases to the thickness of Phanerozoic sedimentation, which generally increases from the continental interior (platform) towards the thick outer margin of the miogeocline. Consequently, the presence of skarn tungsten in the inferred thick margin of the miogeocline might be expected. The virtual restriction of skarn tungsten deposits throughout the cordillera to a belt lying astride or just inside the craton boundary, as shown on the map, strongly supports the Newberry and Einaudi (1981) argument. These authors suggest that the search for tungsten skarns in the cordillera should focus on areas with contact aureoles that formed at moderate depths (5–15 km), as could be expected in the outer reaches of a craton draped with miogeoclinal sediments, rather than seeking out tungsten-enriched calc-alkaline plutons. This suggestion strongly implies that the magma from which almost any deeply buried pluton was formed probably contained sufficient tungsten to form a skarn deposit, given access to reactive carbonate rocks in a relatively high pressure-temperature environment. Under these circumstances, the tungsten must have come from the same source as the magma, most likely generated by a partly melted slab of oceanic crust in a subduction zone.



EASTERN BELT

The eastern belt of tungsten deposits is situated very near the east boundary of highly disrupted cratonal crust that marks the limit of calc-alkaline magmatism and tectonism, which perhaps was produced by a flat-dipping subducting slab (Coney and Reynolds, 1977; Bookstrom, 1981) before its dip steepened and it began a rapid westward retreat about 40 Ma. The deposits in the eastern belt include veins, porphyry by-products, and disseminations. The most productive deposits have been veins and by-product tungsten associated with the Climax porphyry-molybdenum deposit in Colorado (lat 39° N., long 106° W.). The most productive vein deposits have been those near the junction of the Colorado mineral belt and the Rocky Mountain front. According to Tweto (1968), these veins are of post-Laramide age and consequently are much younger than the skarn deposits of the western tungsten belt. The Climax deposit is also post-Laramide in age, formed about 30 Ma. Bookstrom (1981), noting that circular calderas, cylindrical diapirs, and radial and concentric dike swarms formed typically throughout the Rocky Mountain region between 35 and 10 Ma, believes that the whole region was nontectonic, or perhaps was under extensional stress, when the Climax deposit formed. The same conditions probably prevailed when the post-Laramide vein deposits formed.

Other types of tungsten deposits found in several localities along the eastern belt in Colorado and Wyoming are disseminations and small masses in gneiss and other rocks of Precambrian age (Tweto, 1960). The scheelite in most of these deposits contains molybdenum. Few of these deposits have had significant commercial production, but Tweto (1960) suggested that the tungsten in the economically important Tertiary deposits may have been derived from the tungsten-bearing Precambrian rocks. Evidence of a demonstrable basement source for metals in deposits in younger overlying rocks can only rarely be found, but the association of tungsten and molybdenum in this case is convincing. Whether the source of tungsten in deposits throughout the length of the eastern belt in the United States cordillera was the underlying Precambrian basement rocks is more speculative.

The eastern belt in Canada comprises anatectic granitoid plutons of the Omineca Crystalline belt, which were generated from Proterozoic to upper Paleozoic miogeoclinal sedimentary rocks and were overthrust by volcanic and sedimentary rocks between the time of their accretion in the Jurassic until the Cretaceous. Source of the tungsten and molybdenum apparently is the miogeoclinal sedimentary protoliths of the anatectic plutons. These are predominantly *S*-type granites as opposed to the *I*-type granites involved with the vein and greisen tungsten-bearing deposits where the host rocks are predominantly island-arc-type volcanic rocks. The Sierra Nevada tungsten skarns are also related to *I*-type granites.

OIL AND GAS

Oil and gas generally occur in tectonostratigraphic environments that are not favorable for metallic mineral deposits. Sedimentary basins in which rocks are only slightly to moderately deformed, are not intruded by igneous rocks, and are unmetamorphosed or only slightly metamorphosed are favorable environments. As shown on the map, the localization of most of the larger oil and gas fields in the highly deformed and intruded marginal parts of the North American craton is striking. Other large fields, such as those in the Gulf of Mexico, are on the trailing edge of rifted continental margins. Commercial deposits of oil and gas are not known in accreted terranes, but some very important fields, such as those in central and southern California (lat 36° N., long 120° W.), occupy postaccretionary basins. Such basins are sporadically distributed within the collage of accreted terranes and may have formed in part as a result of the accretionary process. The distribution of oil and gas deposits on this map is greatly simplified from an unpublished draft of the energy resource map of the Circum-Pacific Region, northeast quadrant.

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[illegible] Lang (1952) reports that basic rocks including amphibolite, basalt, and diabase dikes are the favorable host rocks for many uranium deposits, but believes the source of the uranium was "acid" magmas. Ruzicka (1971) concurs with this belief but adds that argillaceous sediments might also be a source.

Most of the vein deposits in the Precambrian shield of central Canada are localized along faults, shear zones, fracture systems, and igneous contacts (Lang, 1952); and Lang (1970), observing the dominance of northeast trends, postulates a series of northeast-trending lineaments, some 1,500 km long. A number of these postulated northeast-trending lineaments are within and follow the trend of greenstone belts.

In the western United States most uranium deposits of commercial value are epigenetic sedimentary deposits hosted by lenticular sandstone beds that range in age from the middle Paleozoic to the Pliocene (Finch, 1967; Young, 1978). The major host sandstones are of Triassic and Jurassic age. Most deposits are tabular layers that nearly parallel bedding (Finch, 1967). The host sandstones are thought to have formed mainly in continental environments such as successor basins, shallow depressions, intermontane basins, and coastal plains. Closely related to these peneconcordant epigenetic deposits are discordant "roll" and vein deposits that represent uranium derived from host sandstones and redistributed, mainly by oxygenated ground waters.

Uranium deposits in the western United States show a wide variation in isotopic ages. Data presented by Finch (1967) for 12 Colorado Plateau deposits show lead ages ranging from about 295 to 54 Ma. Rosenburg and Hooper (1982) report fission-track ages of about 6.7 Ma for redistributed sandstone-hosted uranium ore in the Grants mineral belt, New Mexico (lat 35° N., long 107° W.), and ages as young as 11,000–150,000 years are reported for some unoxidized uranium minerals in Wyoming north of lat 40° N. (Finch, 1967).

Of the numerous hypotheses that have been proposed for the origin of the sandstone-hosted uranium, it appears that Gruner's (1956) thesis of multiple migration-accretion, endorsed by Garrels (1957) and Finch (1967), best fits the widespread distribution of uranium and the scarcity of igneous rocks that characterize the epigenetic uranium deposits. This hypothesis holds that the source of uranium was the large volume of Precambrian rocks that were eroded in post-Pennsylvanian time, which could have provided at least 400 million tons of uranium. Gruner (1956) believes that given an interior basin environment, arid or semiarid conditions, and no access to the sea, this uranium could have been leached by Ca, Mg, or Na bicarbonates, and carried long distances in CO_2-rich groundwaters to sites where reducing conditions were met. Concentration of large deposits of uranium could result, according to Gruner, from several stages of oxidation-solution-migration-accretion.

The abundance of uranium and the similarity in age and lithology of Precambrian host rocks in the Canadian shield and the Rocky Mountain front range noted by Nash and others (1981) suggest the continuation of similar, probably uranium-rich Precambrian terranes beneath the western United States and seems to strongly support Gruner's thesis that the primary source of uranium is Precambrian rocks. Moreover, the mechanism they propose for its leaching, transport, and deposition explains convincingly the extremely broad distribution of sandstone-hosted deposits as well as the wide variation in their ages.

LEAD AND ZINC

Four main types of lead-zinc deposits are shown on the map. One is sediment-hosted exhalative massive sulfides, of which the Sullivan deposit in southern British Columbia, near lat 50° N., long 116° W., is perhaps the best known North American example. A second type is the mainly carbonate-hosted deposits such as in the western United States at Metaline, Wash., Tintic, Utah, and Darwin, Calif. Vein deposits typified by those of the Coeur d'Alene district of Idaho (lat 47° N., long 116° W.), and replacement (skarn, manto, chimney) deposits of the Sierra Madre Oriental in Mexico constitute a third major type. Volcanogenic massive sulfide deposits, mainly in the Canadian shield, that have yielded zinc and lead as the principal metals represent a fourth type. Only the first two types of lead-zinc deposits are discussed in this section.

SEDIMENT-HOSTED LEAD-ZINC DEPOSITS

Most of the known sediment-hosted (exhalative) massive sulfide lead-zinc deposits in the North America Cordillera are in British Columbia, the Northwest Territories, Yukon, and Alaska. Others occur in the vicinity of lats 43° and 44° N., and long 115° W. in the United States, but none have been identified south of the Snake River Plain (about lat 42°N.). The sediment-hosted massive sulfide deposits are restricted to the craton in Canada, but the deposits near long 115° W. in the United States are in allochthonous accreted sedimentary rocks. The Sullivan ore body, described by Hamilton and others (1983), is close to the craton boundary in silicastone rocks of Middle Proterozoic age. MacIntyre (1983) describes similar deposits in the Gataga district of northeastern British Columbia (not shown on map) as being hosted in lower Paleozoic deep-marine clastic sedimentary rocks that accumulated in structurally controlled basins and troughs located along the west margin of the North American craton from Cambrian to Late Devonian time.

According to an empirical model developed by Large (1983), the typical host environment for this deposit type is an epicratonic basin bounded by high-angle faults on one or both sides. Subsidence of the basin was controlled by faulting, and the mineral deposits are commonly close to these fault zones. First, second, and third order basins are recognized by Large (1983). The third order basins are smallest, measuring only a few hundred meters to a few kilometers in lateral extent, and are the morphological traps in which the stratiform sulfides accumulated. Many of the deposits contain abundant barite and chert as well as the sulfide ore minerals, and most contain significant amounts of silver. The deposits formed synchronously with their enclosing sediments at the time of basin sedimentation and result probably from hydrothermal fluids circulating in a convection cell and issuing as metal-laden brines from tectonically controlled discharge vents on the seafloor.

Inasmuch as the exhalative massive-sulfide deposits formed syngenetically with sedimentary rocks ranging in age from Middle Proterozoic to Carboniferous, they predate any recognized accretionary (compressional) episode in the western cordillera. Their morphology and depositional environment suggest formation in an extensional tectonic regime punctuated by episodes of rifting, a condition that Hutchinson (1980) noted was characteristic of Middle Proterozoic, and which may have persisted until the middle Paleozoic.

replacement deposits, and contact metasomatic deposits, in the terminology of [illegible] others (1973). All replacement deposits are veins or veinlike. The stratabound deposits presumed epigenetic origin are restricted to one or more (commonly carbonate) stratigr entities with no apparent igneous associations, whereas the replacement deposits, thou many respects similar, are commonly associated with intrusive rocks.

Carbonate-hosted deposits are restricted to miogeoclinal and platform rocks of the crato They commonly occur in brecciated dolomite host rock in a zone of rapid lithological changes, such as between a sedimentary basin edge or a reef front and the tectonically platform. Their distribution from northern Alaska southward throughout the cordiller Mexico and Guatemala reflects this relation. A notable exception is the Leadville d Colorado (lat 39° N., long 106° W.)

Other important deposits and districts located east of the cordillera (not shown on the include Pine Point and Polaris, Northwest Territories; Newfoundland Zinc; and the Vibur Trend and Old Lead Belt districts, Missouri.

As observed by Sangster (1984), no consensus exists on genetic models for carbo hosted lead-zinc deposits, or on ore controls and guides. However, Sangster states that o or more of the following features are commonly associated with these deposits: (1) seco breccia in dolomite, cemented by white sparry dolomite, (2) unconformities within carb sequence (ore horizon will be below unconformities, (3) reefs, (4) carbonate-shal limestone-dolomite facies changes, (5) basement high(s), (6) open spaces of any type within carbonate sequences, especially those formed by karstification as evidenced by brecc thinning of carbonate strata, and local increase in concentration of insoluble residue materi

VOLCANOGENIC MASSIVE-SULFIDE DEPOSITS INCLUDING COPPER, LEAD, AND ZINC

Massive-sulfide deposits with volcanogenic associations are known from Alaska to M Those deposits of Phanerozoic age are either exclusively in, or closely associated with, vo rocks of submarine origin or with related sedimentary rocks of submarine origin. Such de are restricted to accreted terranes composed of island-arc or oceanic crust. Massive-su deposits in Precambrian rocks of the craton are in greenstone belts that probably ar manifestations of similar pre-Phanerozoic accretionary continental growth. Inasmuch as it is now generally accepted that the massive-sulfide deposits formed syngenetically with enclosing host rocks, these deposits in Precambrian rocks are of preaccretionary age, alth some may have been modified by thermal events accompanying or following accretion.

Two major types of massive-sulfide deposits having markedly different lithologic affi and sulfide mineralogy are found in the accreted terranes. One type is typically found in rocks of calc-alkaline affinity in island-arc terranes; the other type is associated with th or calc-alkaline, predominantly mafic volcanic rocks of deeper ocean or marginal-basin The deposits in island-arc terranes are by far the most common. They are typically host submarine flows, tuffs, and breccias of silicic to intermediate composition or by sedim rocks closely associated with mafic to silicic volcanic rocks. Major sulfide minerals are chalcopyrite, sphalerite, and, less commonly, galena, pyrrhotite, and magnetite. Si present in tetrahedrite or tennantite, and gold occurs in its native form. The proportions sulfide minerals may differ widely from one district to another or even from one dep another, and one or more mineral may be absent in some deposits. Quartz as a g mineral is ubiquitous, and sulfate minerals such as barite and anhydrite are locally co A feeder stockwork or pipe consisting of a network of sulfide veinlets in chloritized ho is characteristic of many (proximal) deposits (Large, 1977), but other sulfide bodies b to have formed in seafloor basins (distal) have no such stockwork.

There is now general agreement that the massive-sulfide deposits in island-arc te formed at fracture controlled submarine volcanic centers during late stages of volcanic above a subducting slab. Such deposits form in an extensional tectonic environment submarine fumaroles or hot springs debouched metal-laden brines on or very closely b the seafloor (Sillitoe, 1973). Intrusion and extrusion of igneous melts, especially o composition, are commonly controlled by the same fracture system. The common posi the sulfide bodies at or near the top of a differentiated volcanic pile indicates that the rich brines could well be a final product of magma differentiation; but a more probable may have been metals leached from volcanic rocks lower in the pile by a hydrot convection system that dispelled its flow in or near the central volcanic conduit.

Deposits genetically related to oceanic basalt and found in accreted oceanic-crust ter commonly referred to as Cyprus-type deposits, are not abundant in the northeast qu of the Circum-Pacific, but a few such deposits of diverse Phanerozoic ages are known western United States, western Canada, and southern Alaska. They are typically pyritic with chalcopyrite the principal ore mineral, sphalerite in relatively minor amounts, and quantities of cobalt, lead, gold, and silver. They are believed to have formed at ocea or back-arc spreading centers from mantle-derived magma by processes much like th that formed the deposits hosted in the more silicic island-arc rocks.

Although most volcanogenic massive-sulfide deposits have yielded copper as their pr base metal, many deposits of this type also contain substantial amounts of zinc and l well as precious metals. In the Canadian shield some of the polymetallic massive- deposits have been worked mainly for lead and zinc, and these areas are shown on map

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MANGANESE

Manganese deposits in the western cordillera of North America are largely but not entirely restricted to the area between lat 17° N. in Mexico and lat 50° N. in southern Canada. Outside the cordillera, the main deposits of significance are in Cuba.

The deposits are grouped into three types, following the terminology of Dorr and others (1973)—volcanogene (manganiferous chert), sedimentary, and hypogene (vein). The three types are to some extent intergradational, and all are modified to some degree by supergene processes. The volcanogene deposits, are characteristic of accreted oceanic-crust terranes where most such deposits are found. They are typically in discrete layers within thick piles of volcanic rocks and may be either sharply lenticular or stratiform (Dorr and others, 1973). Many deposits of this type in the California Coast Ranges and elsewhere are associated with chert and consist largely of manganese silicate minerals. Other areas containing volcanogene deposits are in the Washington Olympic Peninsula south of the lat 48° N. and in western Mexico and eastern Cuba close to lat 20° N.

The sedimentary manganese deposits may be oxides or carbonates. Most of the large bedded manganese deposits of the world are marine sedimentary deposits of Precambrian age, but those in the Circum-Pacific northeast quadrant are probably late Phanerozoic in age and associated with fresh water lake beds. The most productive deposit of this type is the Molango (carbonate) deposit, located in continental crust rocks, about lat 21° N. in eastern Mexico. Other fairly large deposits of lower grade are found in the craton near lat 34° N. in southwestern United States.

Hypogene deposits are mostly veins restricted to the craton, including postaccretionary volcanic rocks in the craton. A few replacement deposits are found in the western United States, such as the Leadville deposit in Colorado and the Philipsburg deposit in Montana. Overall production from these deposits has been small, and in many of the hypogene deposits manganese is accompanied by base and/or precious metals.

Dorr and others (1973) state that the source of manganese in all these deposits was either manganiferous mafic minerals in igenous rocks, or manganese enriched magmas, but much disagreement exists as to the relative importance of these sources and as to the number and kinds of concentration processes to which the manganeses has been subjected. However, it appears that the ultimate source of manganese in nodules on the Pacific Ocean seafloor was probably volcanic. Moreover, restriction of land-based deposits in postaccretionary rocks in the cordillera to the area almost directly east ("downstream" as it were) of the subducting nodule-laden Pacific Ocean floor indicates manganese enrichment of oceanic volcanic rocks.

FLUORSPAR

Fluorspar vein deposits in the western cordillera are almost entirely in the craton. They are present in the region between lats 21° N. and 60° N. There are apparently no known fluorspar deposits in Alaska, southern Mexico, and Central America, but a fairly well defined belt of small deposits is present in cratonal rocks of Colombia.

In the western United States, Lamarre and Hodder (1978) describe two curvilinear belts of fluorspar deposits—a western and an eastern belt. Their western belt seems to be based mainly on small occurrences; productive deposits are widely spaced, and consequently we do not include their western belt as a continuous belt on the map. However, their eastern belt corresponds closely with our well-defined fluorspar belt, which extends from approximately lat 42° N., long 106° W. southward to central Mexico.

Van Alstine (1976) argues that major fluorspar deposits are localized chiefly near continental rift zones and lineaments, a contention well supported by the 45 fluorspar deposits associated with the Rio Grande graben, a principal part of the eastern belt.

Lamarre and Hodder (1978) and Cumming and others (1979) observed that fluorspar deposits in the western United States and in northern Mexico are spatially associated with alkalic igneous rocks and are middle and late Tertiary in age. According to Lamarre and Hodder (1978), two fluorspar belts "are situated above the deepest parts of the two postulated early to middle Tertiary subduction zones. * * * Fluorine may have been concentrated in alkalic magmas generated along these subducton zones, carried through the crust as SiF_4, and deposited as CaF_2." In Lamarre and Hodder's view, the fluorine was derived from mineral components of the slab through processes related to partial melting of a subducting slab of oceanic lithosphere.

On the other hand, Clark and others (1982) show high initial strontium-isotope ratios in alkalic intrusions spatially related to fluorspar deposits in the Trans Pecos of west Texas. They believe such ratios strongly suggest crustal contamination of the alkalic magmas, possibly from underlying Precambrian rocks, and they imply that fluorine from these rocks may have enriched the alkalic magmas.

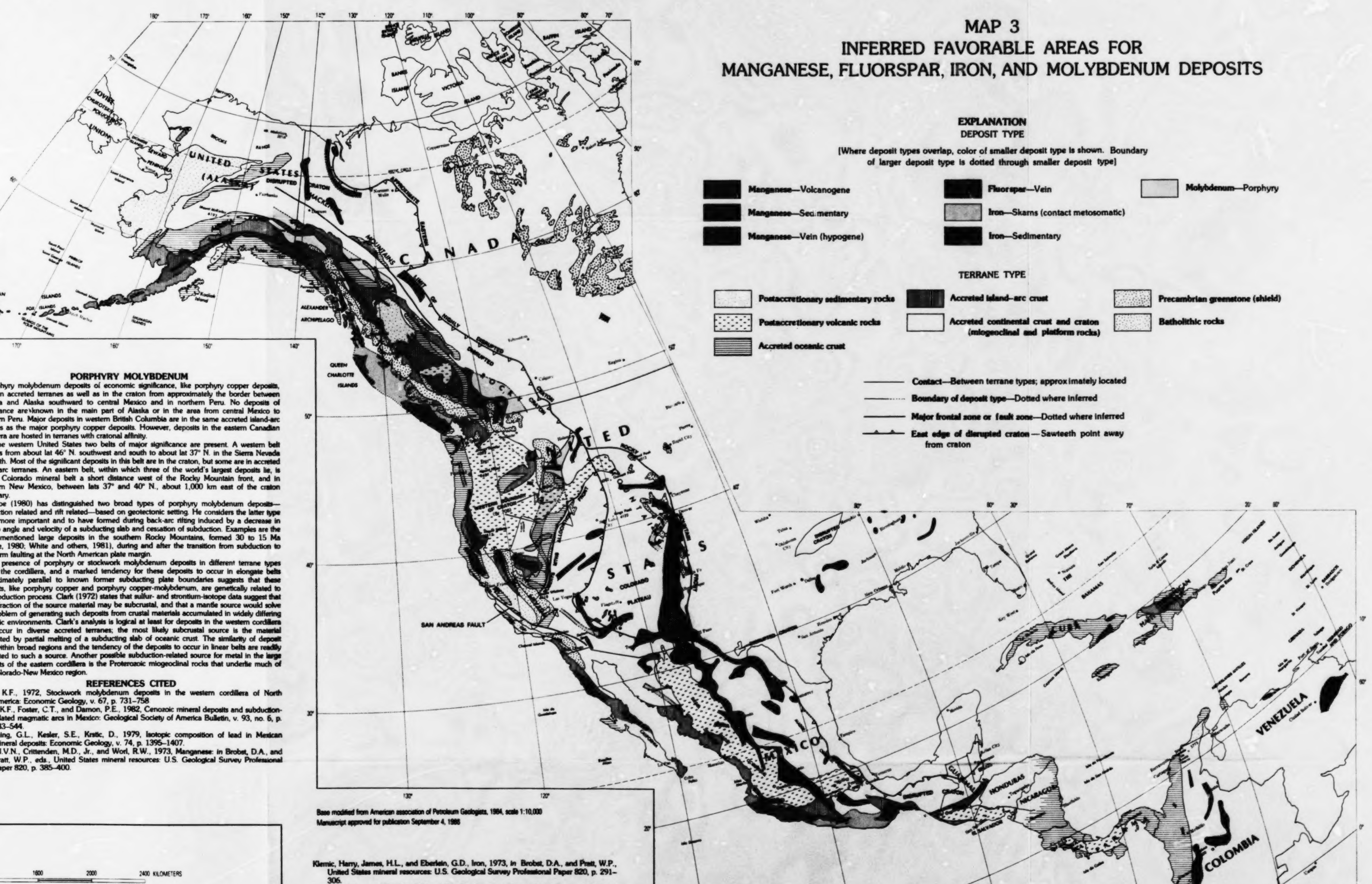
IRON

Iron skarns (contact metasomatic deposits) are prominent in island-arc terranes in southwestern and southern Alaska, western British Columbia, western Nevada, and Mexico, but important deposits are found also in cratonal rocks in southwestern Utah and southeastern California. Iron skarn deposits have not been reported in Central America where island-arc terranes are rare. The conspicuous presence of such skarns in island-arc terranes above former sites of partly melted subducted slabs is to be expected, and skarn deposits in continental crust doubtless resulted from subduction events beneath the craton. The iron in the continental crust deposits may have been derived either from partial melting of a slab, or alternatively, from iron-rich Precambrian crustal rocks within the zone of thermal activity.

The iron skarn deposits of the western cordillera range in age from mid-Permian to late Oligocene or early Miocene. The oldest deposits are associated with 260 Ma old granitoid bodies in northern California. Next oldest are the skarns of British Columbia (Sangster, 1969), related to intrusive rocks mainly of Middle and Late Jurassic age. The Mexican skarns are apparently related mainly to Early Cretaceous igneous rocks, although some may be as young as Eocene. Skarns in Vancouver Island, British Columbia, are preaccretionary in age with respect to their Cretaceous island-arc host terrane. Skarns in southeastern California and western Nevada (Reeves and Kral, 1955; Reeves and others, 1958) are chiefly Late Cretaceous in age, while those in northern Nevada are Eocene or Oligocene in age (Shawe and others, 1962). The youngest skarns are in the Iron Springs district of Utah where laccolithic quartz monzonite bodies of late Oligocene or early Miocene age intrude Jurassic limestone (Klemic and others, 1973). Skarns were apparently produced during at least half a dozen thermal events in western North America over a span of time exceeding 230 Ma.

Sedimentary iron deposits occur in rocks of Precambrian and Phanerozoic age, and nearly all such deposits are in the craton. Significant deposits of sedimentary iron occur in Late Proterozoic and Cretaceous sedimentary rocks of northern Yukon.

MAP 3
INFERRED FAVORABLE AREAS FOR MANGANESE, FLUORSPAR, IRON, AND MOLYBDENUM DEPOSITS



EXPLANATION

DEPOSIT TYPE

[Where deposit types overlap, color of smaller deposit type is shown. Boundary of larger deposit type is dotted through smaller deposit type]

■ **Manganese**—Volcanogene
■ **Manganese**—Sedimentary
■ **Manganese**—Vein (hypogene)
■ **Fluorspar**—Vein
▨ **Iron**—Skarns (contact metosomatic)
■ **Iron**—Sedimentary
☐ **Molybdenum**—Porphyry

TERRANE TYPE

░ **Postaccretionary sedimentary rocks**
░ **Postaccretionary volcanic rocks**
▤ **Accreted oceanic crust**
■ **Accreted island–arc crust**
☐ **Accreted continental crust and craton (miogeoclinal and platform rocks)**
░ **Precambrian greenstone (shield)**
░ **Batholithic rocks**

Contact—Between terrane types; approximately located
Boundary of deposit type—Dotted where inferred
Major frontal zone or fault zone—Dotted where inferred
East edge of disrupted craton—Sawteeth point away from craton

PORPHYRY MOLYBDENUM

Porphyry molybdenum deposits of economic significance, like porphyry copper deposits, occur in accreted terranes as well as in the craton from approximately the border between Canada and Alaska southward to central Mexico and in northern Peru. No deposits of significance are known in the main part of Alaska or in the area from central Mexico to northern Peru. Major deposits in western British Columbia are in the same accreted island-arc terranes as the major porphyry copper deposits. However, deposits in the eastern Canadian cordillera are hosted in terranes with cratonal affinity.

In the western United States two belts of major significance are present. A western belt extends from about lat 46° N. southwest and south to about lat 37° N. in the Sierra Nevada batholith. Most of the significant deposits in this belt are in the craton, but some are in accreted island-arc terranes. An eastern belt, within which three of the world's largest deposits lie, is in the Colorado mineral belt a short distance west of the Rocky Mountain front, and in northern New Mexico, between lats 37° and 40° N., about 1,000 km east of the craton boundary.

Sillitoe (1980) has distinguished two broad types of porphyry molybdenum deposits—subduction related and rift related—based on geotectonic setting. He considers the latter type to be more important and to have formed during back-arc rifting induced by a decrease in the dip angle and velocity of a subducting slab and cessation of subduction. Examples are the above-mentioned large deposits in the southern Rocky Mountains, formed 30 to 15 Ma (Sillitoe, 1980; White and others, 1981), during and after the transition from subduction to transform faulting at the North American plate margin.

The presence of porphyry or stockwork molybdenum deposits in different terrane types within the cordillera, and a marked tendency for these deposits to occur in elongate belts approximately parallel to known former subducting plate boundaries suggests that these deposits, like porphyry copper and porphyry copper-molybdenum, are genetically related to the subduction process. Clark (1972) states that sulfur- and strontium-isotope data suggest that some fraction of the source material may be subcrustal, and that a mantle source would solve the problem of generating such deposits from crustal materials accumulated in widely differing geologic environments. Clark's analysis is logical at least for deposits in the western cordillera that occur in diverse accreted terranes; the most likely subcrustal source is the material generated by partial melting of a subducting slab of oceanic crust. The similarity of deposit ages within broad regions and the tendency of the deposits to occur in linear belts are readily attributed to such a source. Another possible subduction-related source for metal in the large deposits of the eastern cordillera is the Proterozoic miogeoclinal rocks that underlie much of the Colorado-New Mexico region.

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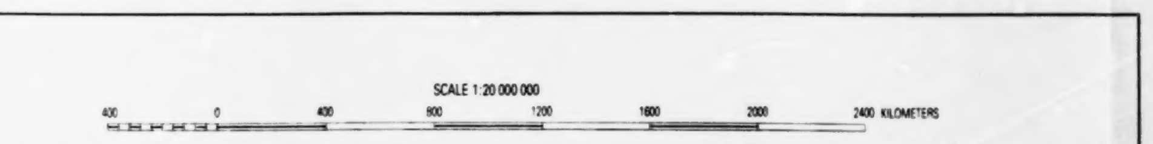

METALLOGENIC MAPS OF THE NORTHEAST QUADRANT OF THE CIRCUM-PACIFIC REGION, SHOWING INFERRED MINERAL BELTS AND DISTRIBUTION OF OIL AND GAS FIELDS IN ACCRETED TERRANES AND CRATON

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PORPHYRY COPPER AND PORPHYRY COPPER-MOLYBDENUM DEPOSITS

The porphyry copper deposits, including those containing significant gold, and the porphyry copper-molybdenum deposits, are variants of a single deposit type and are grouped together on map 4. They are generally associated with hypabyssal calc-alkalic intrusions ranging in composition from quartz monzonite to diorite (Hollister, 1978).

It is evident from their distribution from north to south that while the porphyry-type deposits are not characteristic of any one type of terrane over the expanse of the northeast quadrant of the Circum-Pacific, they are nevertheless restricted to individual terrane types within specific large regions. Porphyry deposits in Alaska are in two belts, one in accreted island-arc terrane and the other in the craton, whereas the deposits in British Columbia are confined almost entirely to accreted island-arc terranes. The majority of porphyry-type deposits in the western United States and northern Mexico are in the craton; exceptions are deposits at Yerington, Nev. (lat 42° N., long 124° W.), and at Lights Creek, Calif. (lat 39° N., long 120° W.), which are in accreted island-arc terranes. Largely undeveloped porphyry-type deposits in southern Mexico are hosted in island-arc terrane, while those in Panama, Colombia, and Ecuador are in accreted oceanic crust terrane as far south as 4° S. latitude. Beyond that, to the south edge of the map at lat 10° S., several large porphyry copper-molybdenum deposits are in the continental margin magmatic arc of the craton. Although porphyry deposits hosted in each of the three major types of terranes have distinctive geologic features, it is apparent that physical and compositional features of the deposits show a common thread throughout the length of the cordillera, suggesting a similar genesis for the deposits and probably a common source for the metals.

The age of porphyry deposits within the western cordillera ranges from Triassic to the late Tertiary. The age range in the southwestern United States and northern Mexico is remarkably narrow (about 20 Ma), whereas deposits in central British Columbia show an overall range of about 163 Ma and a clustering within perhaps six rather distinct age groups (Christopher and Carter, 1976). The oldest porphyry copper deposits in the northeast quadrant of the Circum-Pacific (British Columbia) formed slightly more than 200 Ma, or about the time of the opening of the Atlantic Ocean, which may indicate a possible genetic relationship between plate movement and the formation of porphyry-type deposits. This time (~200 Ma) is slightly prior to accretion of the host terranes in Early and Middle Jurassic time, therefore, the oldest British Columbia porphyries are preaccretionary in age.

At least 90 percent of the porphyry deposits in the southwestern United States and northern Mexico, and a high percentage of such deposits in British Columbia, the Caribbean, and in the western United States were formed during the Laramide orogeny, a relatively short span of time lasting from about 80 to 40 Ma (Coney, 1976). Age differences within the Laramide interval probably result from migration of a magmatic arc above a shallow, gently-dipping subducting slab.

The marked tendency for the porphyry-type deposits to occur in elongate belts inboard from present or former subducting plate boundaries indicates that these deposits are genetically related to the subduction process. No so easily explained is the tendency for some porphyry-type deposits to occur in clusters in the southwestern United States and central British Columbia, or the occurrence of such isolated very large deposits as those at Butte, Bingham, and Ely in the western United States. The answer to this question may be control by large, intersecting fracture systems penetrating the entire thickness of the crust. Also, some porphyry deposits may be buried by young cover rocks, in which case clustering might be only an apparent phenomenon.

Sillitoe (1972) has presented a cogent argument that porphyry deposits constitute a normal facet of calc-alkaline magmatism, and that the components of calc-alkaline igneous rocks and porphyry deposits are generated by partial melting of oceanic crustal rocks in underlying subduction zones at the elongate compressive juncture between lithospheric plates. He argues further that the only source of metals available to all porphyry copper deposits, taking into consideration the thin crust and almost total absence of sialic crust beneath some copper provinces (such as the Solomon Islands), would seem to be the upper mantle, the probable ultimate source of metals in virtually all mineral deposits. Burnham (1981) points out that during metamorphism of oceanic basalt containing an average of 77 parts per million (ppm) copper and 1,000 ppm FeS during subduction, nearly all the copper would combine with the FeS to form a pyrrhotite solid solution that would dissolve and provide an ample source of copper for porphyry deposits upon melting of the amphibolite. Burnham (1981) concludes "it is unnecessary to call upon abnormally copper-rich rocks, such as the metalliferous sediments of the Nazca plate (or copper-rich Precambrian basement rocks), for the sources of ore-bearing magmas."

This argument is most convincing for the numerous deposits that lie inboard a reasonable distance (150–250 km) from present or former trenches of subduction zones. However, a rational explanation for distant relatively isolated deposits hundreds of kilometers from such trenches is more elusive. Coney and Reynolds (1977) tracked the systematic variation in the radiometric ages of Cretaceous and Tertiary igneous rocks, and concluded that the dip of the Benioff zone (subducting slab) flattened progressively beneath southwestern North America during the interval beneath 130–110 Ma and about 55–40 Ma. The decrease in dip is believed due to a high rate of convergence—the higher the rate, the lower the angle of dip. If this analysis is correct, the copper and other metals in the great porphyry deposits of Butte, Bingham, and Ely could have come from partial melting of shallow-dipping relatively fast-moving subducting slabs. Further support for this argument is that similarities in general geochemistry of intrusive rocks associated with porphyry copper deposits and style of porphyry copper mineralization in continental terranes, compared to that in island-arc terranes, suggest that the magmas in both types of terranes were probably largely derived beneath the crust, and that continental contamination contributed insignificantly to the magma or metals (Mitchell and Garson, 1981).

One further point worth noting is that, while most deposits of the porphyry type appear in general to be spatially related to a subduction zone and hence to a compressional tectonic regime, it is also evident that a high percentage of porphyry deposits are localized at or near the intersection of important fracture systems, one system commonly being strike slip, and the other extensional dip slip (Hollister, 1978; Titley, 1982). This is further borne out by the presence of abundant dikes closely associated with porphyry copper deposits, which clearly indicates an extensional environment at the time of intrusion and mineralization. The favored structural environment in which many porphyry systems were emplaced would thus appear to be tensional, at least at the level of emplacement.

TIN

Deposits of tin in the northeast quadrant of the Circum-Pacific are sparse, widely scattered, and small. The few deposits that have produced tin are widely separated localities from the Seward Peninsula in Alaska to central Mexico. Some tin has been produced as a by-product in the production of other metals, mainly from the Sullivan lead-zinc mine in southern Canada (lat 50° N.). All the deposits that have produced tin are in the craton, but unproductive occurrences of tin are present in accreted terranes as well as in the craton.

Sainsbury and Reed (1973) observe that tin deposits are typically associated with rhyolite and biotite-muscovite granite, the so-called "tin granites," and that this association is so well marked on a worldwide scale that there seems little likelihood of finding significant tin in other geologic environments. Inasmuch as such rocks are characteristic of the craton, it is obvious that exploration for new-deposit resources of tin in the northeast quadrant should focus on the craton rather than on the accreted terranes. In addition to the tin associated with base metals at the Sullivan mine, the main areas of known tin mineralization are in (1) greisen-like deposits on the Seward Peninsula, Alaska, (2) a belt containing sporadic placer deposits across central Alaska (not shown on map), (3) abundant but small veins and encrustations in rhyolitic rocks in New Mexico and in central Mexico, (4) veins in granitoid and metamorphic rocks in the southern Sierra Nevada batholith, California (Sainsbury, 1969; Cobb, 1960), and (5) small vein, skarn, and greisen deposits in the McQuentin and Cassiar districts of Yukon and British Columbia (not shown on map). As noted by Sainsbury and Reed (1973) the geology of vein tin deposits is well understood, but the genesis of tin deposits and of "tin granite" remains a field for speculation and debate.

SILVER

Silver deposits fall into two broad categories: (1) deposits in which silver is a by-product or co-product produced with other metals, and (2) deposits in which silver is the major constituent. Heyl and others (1973) observed that most of the silver produced results from by-product or co-product production, and they listed nine types of deposits having such production. Chief among these are various types of base-metal deposits. On this map only those deposits in which silver is the major constituent are shown. Essentially, this includes silver-vein and replacement-type deposits. The distribution of silver deposits is thus restricted on this map, and does not reflect the distribution of all silver-bearing deposits.

The vein and replacement deposits occur mainly in areas underlain by continental crust or the craton, but also in some areas in Canada and western United States that are underlain by accreted island-arc terranes. No silver deposits are present in oceanic crust terranes except deposits in which gold is the principal metal. The great "bonanza"-type vein deposits such as Comstock and Tonopah, Nev. in the western United States are in postaccretionary volcanic rocks. At Comstock these host rocks overlie an accreted island-arc terrane, whereas at Tonopah the host rocks overlie continental crust of the craton. Most of the silver deposits that are in postaccretionary volcanic rocks in Mexico are underlain by either craton or accreted continental crust. The giant Coeur d' Alene district deposits near lat 47° N. long 116° W. are in Precambrian cratonal rocks.

In view of the exceedingly broad distribution of silver-bearing deposits, it is difficult to speculate on the source of the metal. Silver evidently can form in a large variety of tectonic environments. As reported by Heyl and others (1973) citing Degens and Ross (1969), seafloor muds of the Red Sea contain lead, zinc, iron sulfides, and some silver in lenticular basins. These metals are being deposited by heated brines rising through the seafloor in the central part of the Red Sea. In the Salton Sea area of southern California brines tapped from a deep drill hole contain notably high concentrations of heavy metals, including silver. Polymetallic sulfide hydrothermal vents of the East Pacific Rise contain 300–5,000 g silver derived from oceanic

SOVIET
UNION
UNITED
(ALASKA)
ALEUTIAN
ISLANDS
180°
170°
160°
150°
70°
60°
50°

tholeiitic volcanoes (Hekinian and others 1980). The source of the silver and other me the Red Sea and Salton Sea may have been a deep magmatic source, as believed by and others (1963), or it may have been derived from leaching of evaporite beds or sediments (Craig, 1969). The uncertainty illustrates the high degree of speculation in id ing the primary source of metals in nearly any type of deposit, even those that can b served forming today. Silver in particular, because of the extremely scattered distributi its deposits, may have come from multiple sources.

BARITE

Deposits of commercial barite have been divided into three main types by Brobst (vein and cavity filling, residual, and bedded. Only the bedded and vein-type deposits a nificant in the northeast quadrant of the Circum-Pacific and they are not differentiated map. Bedded deposits, the most important type commercially, occur in rather well-defin cuate belts in the cordillera from eastern Alaska southward to northern Mexico, and in C bia, South America. No bedded deposits have been identified in the published literature central and southern Mexico or Central America, although Reyna (1956) mentions that barite deposits are present in nearly all parts of Mexico. Some of these may be the b type. Large bedded deposits are also present in the Ouachita Mountains of the south-c United States.

Most bedded barite deposits in western North America are Cambrian to Mississippian i However, some deposits in northern Mexico are as young as Pennsylvanian, and the C bian deposits are in sedimentary rocks of Cretaceous age. In British Columbia and the Y stratiform barite deposits hosted by cratonal Devonian and Mississippian clastic rocks an ally associated with sedimentary exhalative lead, zinc, silver, and barium deposits constitu largest known barite resource in the cordillera. Stratabound barite-fluorite deposits in Dev shelf carbonate rocks of the northern Canadian Rockies also constitute a significant res (Dawson, 1983). In the western conterminous United States, large deposits of bedded are interlayered with radiolarian chert and shaly mudstone of Ordovician and Devonian The large deposits in part of the Roberts Mountains allochthon (Shawe and others 1969) been displaced more than 80 km eastward from their depositional site. Therefore, altho they reside inland from the craton boundary, they formed in accreted oceanic crust ter Devonian and Mississippian deposits in California are in accreted island-arc terranes. bedded deposits in the Ouachita Mountains are chiefly in Devonian and Mississippian shaley rocks (Brobst, 1973), and deposits in northern Mexico are in accreted eugeoclinal ranging in age from Devonian to Early Pennsylvanian (Poole and others 1983). Smaller ded deposits in Colombia are in Mesozoic miogeoclinal sedimentary rocks.

The association of bedded barite with turbidite clastic rocks, dark shale, and chert of water origin and chiefly of middle Paleozoic age is striking. The overall map distribution cates that in areas such as British Columbia, deposition occurred slightly inside the contin margin in elongated fault-bounded basins or grabens. The barite in base-metal districts this region is genetically related to exhalative base-metal sulfide deposits whose source system of submarine hydrothermal events (Dawson and Orchond, 1982). In the wester southern United States and in Mexico, barite is found primarily in allochthonous sedim rocks whose protoliths perhaps originated in back-arc basins outside the continental m Recent seafloor investigations have proven that barite, together with other sulphate, si oxide, and sulfide minerals is deposited from fault-controlled hydrothermal vents in the Clemente fault zone near San Diego, Calif. (Lonsdale, 1979) and along the East Pacifi (not shown on map) (Hekinian and others 1980).

ANTIMONY

Antimony in the northeast quadrant of the Circum-Pacific occurs mainly as veins and i lar replacements in miogeoclinal sedimentary rocks and the granitic rocks that intrude Numerous productive vein deposits also occur in postaccretionary volcanic rocks that o miogeoclinal rocks. Fairly numerous but small deposits in Canada and in the western U States are in island-arc terranes. Two deposits, one in California and one in central British umbia (not shown on map), are associated with mercury in accreted oceanic crust. The l production has come from vein deposits in miogeoclinal rocks and postaccretionary vo rocks in Mexico, and from polymetallic vein deposits in Idaho (lat 45° N., long 117° W.) antimony was a by-product in the production of base and precious metals (Miller, 1 However, antimony is the sole metal produced from some epithermal vein deposits in Ne (approx. lat 40° N., long 119°–116° W.) (Lawrence, 1963) and in Mexico (Reyna, 1956).

The distribution of productive antimony deposits is rather similar to deposits of tin tungsten in that the great majority of deposits are within the craton but fairly close to its boundary, within the apron of miogeoclinal rocks. A discontinuous belt of antimony dep extends from southern Mexico northward to about lat 49° N. Only a few small deposit known in British Columbia (not shown on map). Antimony deposits in Alaska, alth numerous, are all small and of little economic value (not shown on map). In the we United States the antimony belt largely overlaps the areas of tungsten and tin depos Mexico, antimony seems to have no spatial relation to tungsten but lies in a discrete bel of the main belt of tin deposits.

The narrow linear belts of antimony deposits suggest spatial relation to a subduction The spatial association between antimony and tungsten and the similar style in occur within and parallel to the craton suggests that the source of the antimony may have been the same magma regime as the tungsten, that is, from partial melting of a subducting The antimony may have been more fugaceous or less reactive with carbonate rocks tungsten at the deeper crustal levels, and may have moved to higher levels to form characteristic epigenetic deposits.

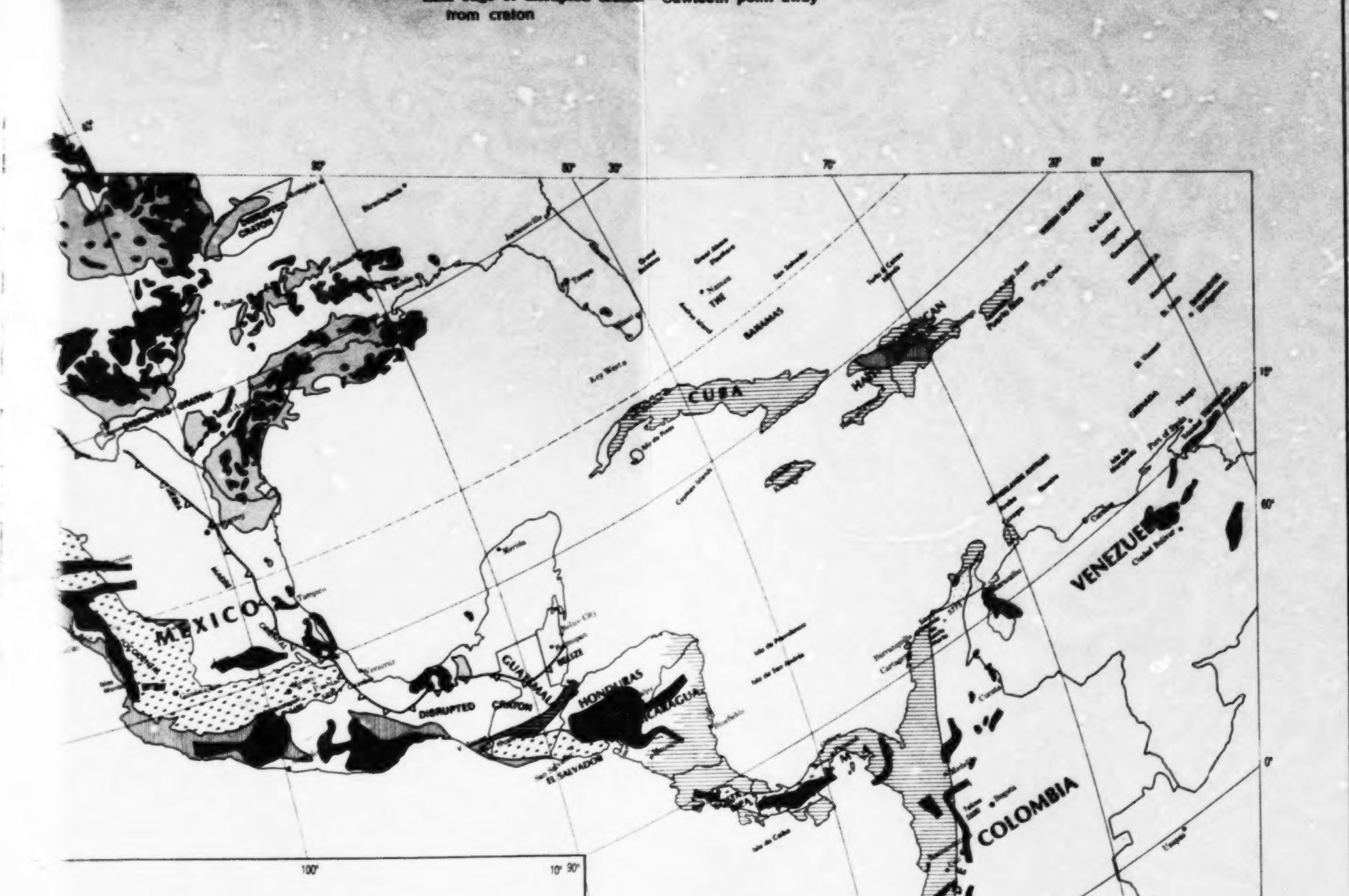
PHOSPHATE

Deposits of phosphate of commercial or potentially commercial value include several (Cathcart and Gulbrandsen, 1973), the most important of which is marine sedime phosphate. Large deposits of this type are located in areas of the craton overlai miogeoclinal rocks from northern Alaska to Mexico and in Colombia. Not all are presen commercial grade. The age of these deposits ranges from Mississippian to Cretaceous largest deposits are in the Phosphoria Formation of Permian age in the western United S Other phosphatic deposits of less economic potential occur in platform rocks of the craton deposits of younger (Miocene) age occur in California, Peru (not shown on map) and a the southeastern United States.

Sedimentary phosphorite occurs in areas where divergent upwelling seawater condi prevail. McKelvey (1963) has shown that in the late Tertiary phosphorite was deposit warm latitudes between lats 40° N. and 40° S., mainly on the west coasts of continents same is true of phosphorite being deposited today. Although older deposits suc Mississippian and Triassic phosphates in northern Alaska show no such clear-cut geogr distribution, Sheldon (1964) has shown that when deposits of ancient phosphorite su these "are located according to their virtual geomagnetic poles, their resulting paleolatitu distribution closely matches the latitudinal distribution of younger phosphorite." Als paleogeographic setting of the ancient phosphorite matches the setting of you phosphorite. Sheldon concludes that paleomagnetic and paleogeographic data can significantly in the search for ancient phosphorite.

Major frontal zone or fault zone—Dotted where inferred

East edge of disrupted craton—Sawteeth point away from craton



s striking. Other large fields, such as those in the Gulf of Mexico, are on the
tted continental margins. Commercial deposits of oil and gas are not known
ranes, but some very important fields, such as those in central and southern
N., long 120° W.), occupy postaccretionary basins. Such basins are sporadi-
within the collage of accreted terranes and may have formed in part as a result
y process. The distribution of oil and gas deposits on this map is greatly sim-
unpublished draft of the energy resource map of the Circum-Pacific Region,
nt.

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Lang (1952) reports that basic rocks including amphibolite, basalt, and diabase dikes are the favorable host rocks for many uranium deposits, but believes the source of the uranium was "acid" magmas. Ruzicka (1971) concurs with this belief but adds that argillaceous sediments might also be a source.

Most of the vein deposits in the Precambrian shield of central Canada are localized along faults, shear zones, fracture systems, and igneous contacts (Lang, 1952); and Lang (1970), observing the dominance of northeast trends, postulates a series of northeast-trending lineaments, some 1,500 km long. A number of these postulated northeast-trending lineaments are within and follow the trend of greenstone belts.

In the western United States most uranium deposits of commercial value are epigenetic sedimentary deposits hosted by lenticular sandstone beds that range in age from the middle Paleozoic to the Pliocene (Finch, 1967; Young, 1978). The major host sandstones are of Triassic and Jurassic age. Most deposits are tabular layers that nearly parallel bedding (Finch, 1967). The host sandstones are thought to have formed mainly in continental environments such as successor basins, shallow depressions, intermontane basins, and coastal plains. Closely related to these penecontemporaneous epigenetic deposits are discordant "roll" and vein deposits that represent uranium derived from host sandstones and redistributed, mainly by oxygenated ground waters.

Uranium deposits in the western United States show a wide variation in isotopic ages. Data presented by Finch (1967) for 12 Colorado Plateau deposits show lead ages ranging from about 295 to 54 Ma. Rosenburg and Hooper (1982) report fission-track ages of about 6.7 Ma for redistributed sandstone-hosted uranium ore in the Grants mineral belt, New Mexico (lat 35° N., long 107° W.), and ages as young as 11,000–150,000 years are reported for some unoxidized uranium minerals in Wyoming north of lat 40° N. (Finch, 1967).

Of the numerous hypotheses that have been proposed for the origin of the sandstone-hosted uranium, it appears that Gruner's (1956) thesis of multiple migration-accretion, endorsed by Garrels (1957) and Finch (1967), best fits the widespread distribution of uranium and the scarcity of igneous rocks that characterize the epigenetic uranium deposits. This hypothesis holds that the source of uranium was the large volume of Precambrian rocks that were eroded in post-Pennsylvanian time, which could have provided at least 400 million tons of uranium. Gruner (1956) believes that given an interior basin environment, arid or semiarid conditions, and no access to the sea, this uranium could have been leached by Ca, Mg, or Na bicarbonates, and carried long distances in CO_2-rich groundwaters to sites where reducing conditions were met. Concentration of large deposits of uranium could result, according to Gruner, from several stages of oxidation-solution-migration-accretion.

The abundance of uranium and the similarity in age and lithology of Precambrian host rocks in the Canadian shield and the Rocky Mountain front range noted by Nash and others (1981) suggest the continuation of similar, probably uranium-rich Precambrian terranes beneath the western United States and seems to strongly support Gruner's thesis that the primary source of uranium is Precambrian rocks. Moreover, the mechanism they propose for its leaching, transport, and deposition explains convincingly the extremely broad distribution of sandstone-hosted deposits as well as the wide variation in their ages.

LEAD AND ZINC

Four main types of lead-zinc deposits are shown on the map. One is sediment-hosted exhalative massive sulfides, of which the Sullivan deposit in southern British Columbia, near lat 50° N., long 116° W., is perhaps the best known North American example. A second type is the mainly carbonate-hosted deposits such as in the western United States at Metaline, Wash., Tintic, Utah, and Darwin, Calif. Vein deposits typified by those of the Coeur d'Alene district of Idaho (lat 47° N., long 116° W.), and replacement (skarn, manto, chimney) deposits of the Sierra Madre Oriental in Mexico constitute a third major type. Volcanogenic massive sulfide deposits, mainly in the Canadian shield, that have yielded zinc and lead as the principal metals represent a fourth type. Only the first two types of lead-zinc deposits are discussed in this section.

SEDIMENT-HOSTED LEAD-ZINC DEPOSITS

Most of the known sediment-hosted (exhalative) massive sulfide lead-zinc deposits in the North America Cordillera are in British Columbia, the Northwest Territories, Yukon, and Alaska. Others occur in the vicinity of lats 43° and 44° N., and long 115° W. in the United States, but none have been identified south of the Snake River Plain (about lat 42°N.). The sediment-hosted massive sulfide deposits are restricted to the craton in Canada, but the deposits near long 115° W. in the United States are in allochthonous accreted sedimentary rocks. The Sullivan ore body, described by Hamilton and others (1983), is close to the craton boundary in silicastone rocks of Middle Proterozoic age. MacIntyre (1983) describes similar deposits in the Gataga district of northeastern British Columbia (not shown on map) as being hosted in lower Paleozoic deep-marine clastic sedimentary rocks that accumulated in structurally controlled basins and troughs located along the west margin of the North American craton from Cambrian to Late Devonian time.

According to an empirical model developed by Large (1983), the typical host environment for this deposit type is an epicrantonic basin bounded by high-angle faults on one or both sides. Subsidence of the basin was controlled by faulting, and the mineral deposits are commonly close to these fault zones. First, second, and third order basins are recognized by Large (1983). The third order basins are smallest, measuring only a few hundred meters to a few kilometers in lateral extent, and are the morphological traps in which the stratiform sulfides accumulated. Many of the deposits contain abundant barite and chert as well as the sulfide ore minerals, and most contain significant amounts of silver. The deposits formed synchronously with their enclosing sediments at the time of basin sedimentation and result probably from hydrothermal fluids circulating in a convection cell and issuing as metal-laden brines from tectonically controlled discharge vents on the seafloor.

Inasmuch as the exhalative massive-sulfide deposits formed syngenetically with sedimentary rocks ranging in age from Middle Proterozoic to Carboniferous, they predate any recognized accretionary (compressional) episode in the western cordillera. Their morphology and depositional environment suggest formation in an extensional tectonic regime punctuated by episodes of rifting, a condition that Hutchinson (1980) noted was characteristic of Middle Proterozoic, and which may have persisted until the middle Paleozoic.

[illegible] (1978). All [illegible] deposits are veins or veinlike. The stratabound deposits of presumed epigenetic origin are restricted to one or more (commonly carbonate) stratigraphic units with no apparent igneous associations, whereas the replacement deposits, though in many respects similar, are commonly associated with intrusive rocks.

Carbonate-hosted deposits are restricted to miogeoclinal and platform rocks of the craton. They commonly occur in brecciated dolomite host rock in a zone of rapid lithological facies changes, such as between a sedimentary basin edge or a reef front and the tectonically stable platform. Their distribution from northern Alaska southward throughout the cordillera to Mexico and Guatemala reflects this relation. A notable exception is the Leadville district, Colorado (lat 39° N., long 106° W.).

Other important deposits and districts located east of the cordillera (not shown on the map) include Pine Point and Polaris, Northwest Territories; Newfoundland Zinc; and the Viburnum Trend and Old Lead Belt districts, Missouri.

As observed by Sangster (1984), no consensus exists on genetic models for carbonate-hosted lead-zinc deposits, or on ore controls and guides. However, Sangster states that one or more of the following features are commonly associated with these deposits: (1) secondary breccia in dolomite, cemented by white sparry dolomite, (2) unconformities within carbonate sequence (ore horizon will be below unconformities, (3) reefs, (4) carbonate-shale and limestone-dolomite facies changes, (5) basement high(s), (6) open spaces of any type within carbonate sequences, especially those formed by karstification as evidenced by brecciation, thinning of carbonate strata, and local increase in concentration of insoluble residue materials.

VOLCANOGENIC MASSIVE-SULFIDE DEPOSITS INCLUDING COPPER, LEAD, AND ZINC

Massive-sulfide deposits with volcanogenic associations are known from Alaska to Mexico. Those deposits of Phanerozoic age are either exclusively in, or closely associated with, volcanic rocks of submarine origin or with related sedimentary rocks of submarine origin. Such deposits are restricted to accreted terranes composed of island-arc or oceanic crust. Massive-sulfide deposits in Precambrian rocks of the craton are in greenstone belts that probably are manifestations of similar pre-Phanerozoic accretionary continental growth. Inasmuch as it is now generally accepted that the massive-sulfide deposits formed syngenetically with their enclosing host rocks, these deposits in Precambrian rocks are of preaccretionary age, although some may have been modified by thermal events accompanying or following accretion.

Two major types of massive-sulfide deposits having markedly different lithologic affiliation and sulfide mineralogy are found in the accreted terranes. One type is typically found in silicic rocks of calc-alkaline affinity in island-arc terranes; the other type is associated with tholeiitic or calc-alkaline, predominantly mafic volcanic rocks of deeper ocean or marginal-basin origin. The deposits in island-arc terranes are by far the most common. They are typically hosted by submarine flows, tuffs, and breccias of silicic to intermediate composition or by sedimentary rocks closely associated with mafic to silicic volcanic rocks. Major sulfide minerals are pyrite, chalcopyrite, sphalerite, and, less commonly, galena, pyrrhotite, and magnetite. Silver is present in tetrahedrite or tennantite, and gold occurs in its native form. The proportions of the sulfide minerals may differ widely from one district to another or even from one deposit to another, and one or more mineral may be absent in some deposits. Quartz as a gangue mineral is ubiquitous, and sulfate minerals such as barite and anhydrite are locally common. A feeder stockwork or pipe consisting of a network of sulfide veinlets in chloritized host rock is characteristic of many (proximal) deposits (Large, 1977), but other sulfide bodies believed to have formed in seafloor basins (distal) have no such stockwork.

There is now general agreement that the massive-sulfide deposits in island-arc terranes formed at fracture controlled submarine volcanic centers during late stages of volcanic activity above a subducting slab. Such deposits form in an extensional tectonic environment where submarine fumaroles or hot springs debouched metal-laden brines on or very closely beneath the seafloor (Sillitoe, 1973). Intrusion and extrusion of igneous melts, especially of felsic composition, are commonly controlled by the same fracture system. The common position of the sulfide bodies at or near the top of a differentiated volcanic pile indicates that the metal-rich brines could well be a final product of magma differentiation; but a more probable source may have been metals leached from volcanic rocks lower in the pile by a hydrothermal convection system that dispelled its flow in or near the central volcanic conduit.

Deposits genetically related to oceanic basalt and found in accreted oceanic-crust terranes, commonly referred to as Cyprus-type deposits, are not abundant in the northeast quadrant of the Circum-Pacific, but a few such deposits of diverse Phanerozoic ages are known in the western United States, western Canada, and southern Alaska. They are typically pyritic bodies with chalcopyrite the principal ore mineral, sphalerite in relatively minor amounts, and minor quantities of cobalt, lead, gold, and silver. They are believed to have formed at ocean-ridge or back-arc spreading centers from mantle-derived magma by processes much like the ones that formed the deposits hosted in the more silicic island-arc rocks.

Although most volcanogenic massive-sulfide deposits have yielded copper as their principal base metal, many deposits of this type also contain substantial amounts of zinc and lead as well as precious metals. In the Canadian shield some of the polymetallic massive-sulfide deposits have been worked mainly for lead and zinc, and these areas are shown on map 2.

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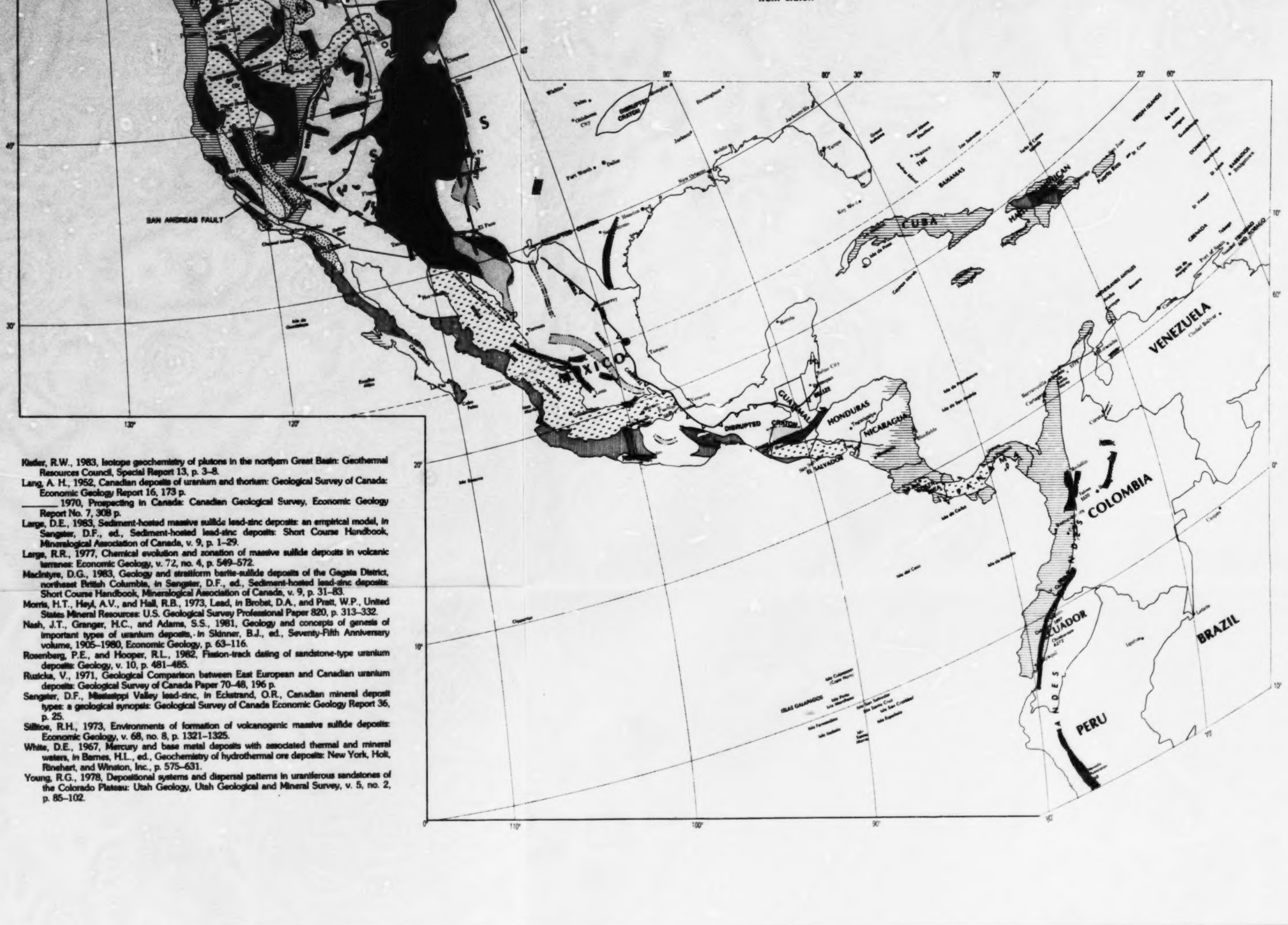
Boundary of deposit type—Dotted where inferred

Major frontal zone or fault zone—Dotted where inferred

East edge of disrupted craton—Sawteeth point away from craton



MAP 3
INFERRED FAVORABLE AREAS FOR MANGANESE, FLUORSPAR, IRON, AND MOLYBDENUM DEPOSITS

EXPLANATION

DEPOSIT TYPE

[Where deposit types overlap, color of smaller deposit type is shown. Boundary of larger deposit type is dotted through smaller deposit type]

- ▨ **Manganese**—Volcanogene
- ■ **Manganese**—Sedimentary
- ■ **Manganese**—Vein (hypogene)
- ■ **Fluorspar**—Vein
- □ **Iron**—Skarns (contact metosomatic)
- ■ **Iron**—Sedimentary
- □ **Molybdenum**—Porphyry

TERRANE TYPE

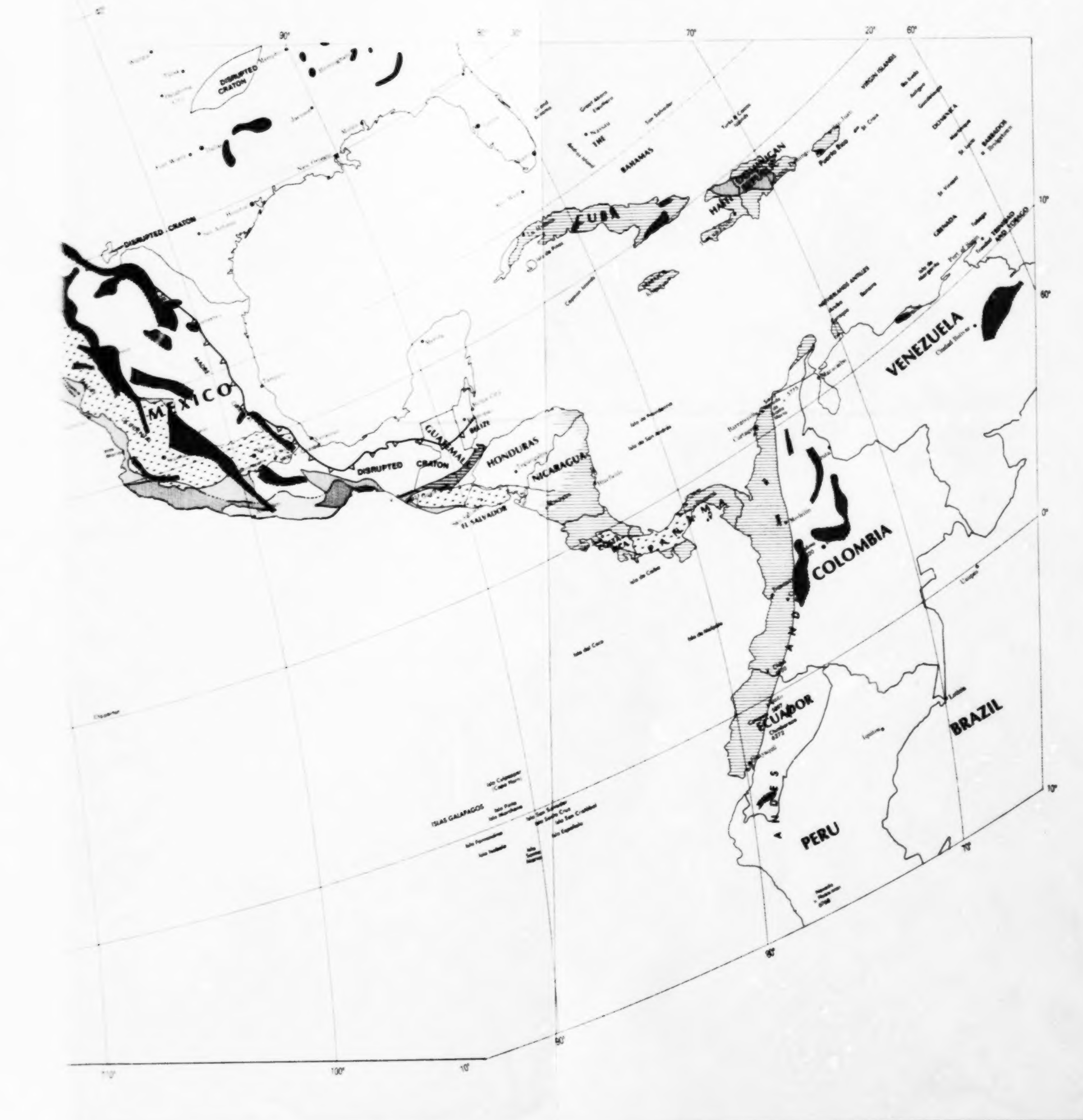
- □ **Postaccretionary sedimentary rocks**
- ▨ **Postaccretionary volcanic rocks**
- ▤ **Accreted oceanic crust**
- ▥ **Accreted island–arc crust**
- □ **Accreted continental crust and craton (miogeoclinal and platform rocks)**
- ▨ **Precambrian greenstone (shield)**
- ▨ **Batholithic rocks**

Contact—Between terrane types; approximately located

Boundary of deposit type—Dotted where inferred

Major frontal zone or fault zone—Dotted where inferred

East edge of disrupted craton—Sawteeth point away from craton



PORPHYRY COPPER AND PORPHYRY COPPER-MOLYBDENUM DEPOSITS

The porphyry copper deposits, including those containing significant gold, and the porphyry copper-molybdenum deposits, are variants of a single deposit type and are grouped together on map 4. They are generally associated with hypabyssal calc-alkalic intrusions ranging in composition from quartz monzonite to diorite (Hollister, 1978).

It is evident from their distribution from north to south that while the porphyry-type deposits are not characteristic of any one type of terrane over the expanse of the northeast quadrant of the Circum-Pacific, they are nevertheless restricted to individual terrane types within specific large regions. Porphyry deposits in Alaska are in two belts, one in accreted island-arc terrane and the other in the craton, whereas the deposits in British Columbia are confined almost entirely to accreted island-arc terranes. The majority of porphyry-type deposits in the western United States and northern Mexico are in the craton; exceptions are deposits at Yerington, Nev. (lat 42° N., long 124° W.), and at Lights Creek, Calif. (lat 39° N., long 120° W.), which are in accreted island-arc terranes. Largely undeveloped porphyry-type deposits in southern Mexico are hosted in island-arc terrane, while those in Panama, Colombia, and Ecuador are in accreted oceanic crust terrane as far south as 4° S. latitude. Beyond that, to the south edge of the map at lat 10° S., several large porphyry copper-molybdenum deposits are in the continental margin magmatic arc of the craton. Although porphyry deposits hosted in each of the three major types of terranes have distinctive geologic features, it is apparent that physical and compositional features of the deposits show a common thread throughout the length of the cordillera, suggesting a similar genesis for the deposits and probably a common source for the metals.

The age of porphyry deposits within the western cordillera ranges from Triassic to the late Tertiary. The age range in the southwestern United States and northern Mexico is remarkably narrow (about 20 Ma), whereas deposits in central British Columbia show an overall range of about 163 Ma and a clustering within perhaps six rather distinct age groups (Christopher and Carter, 1976). The oldest porphyry copper deposits in the northeast quadrant of the Circum-Pacific (British Columbia) formed slightly more than 200 Ma, or about the time of the opening of the Atlantic Ocean, which may indicate a possible genetic relationship between plate movement and the formation of porphyry-type deposits. This time (~200 Ma) is slightly prior to accretion of the host terranes in Early and Middle Jurassic time, therefore, the oldest British Columbia porphyries are preaccretionary in age.

At least 90 percent of the porphyry deposits in the southwestern United States and northern Mexico, and a high percentage of such deposits in British Columbia, the Caribbean, and in the western United States were formed during the Laramide orogeny, a relatively short span of time lasting from about 80 to 40 Ma (Coney, 1976). Age differences within the Laramide interval probably result from migration of a magmatic arc above a shallow, gently-dipping subducting slab.

The marked tendency for the porphyry-type deposits to occur in elongate belts inboard from present or former subducting plate boundaries indicates that these deposits are genetically related to the subduction process. No so easily explained is the tendency for some porphyry-type deposits to occur in clusters in the southwestern United States and central British Columbia, or the occurrence of such isolated very large deposits as those at Butte, Bingham, and Ely in the western United States. The answer to this question may be control by large, intersecting fracture systems penetrating the entire thickness of the crust. Also, some porphyry deposits may be buried by young cover rocks, in which case clustering might be only an apparent phenomenon.

Sillitoe (1972) has presented a cogent argument that porphyry deposits constitute a normal facet of calc-alkaline magmatism, and that the components of calc-alkaline igneous rocks and porphyry deposits are generated by partial melting of oceanic crustal rocks in underlying subduction zones at the elongate compressive juncture between lithospheric plates. He argues further that the only source of metals available to all porphyry copper deposits, taking into consideration the thin crust and almost total absence of sialic crust beneath some copper provinces (such as the Solomon Islands), would seem to be the upper mantle, the probable ultimate source of metals in virtually all mineral deposits. Burnham (1981) points out that during metamorphism of oceanic basalt containing an average of 77 parts per million (ppm) copper and 1,000 ppm FeS during subduction, nearly all the copper would combine with the FeS to form a pyrrhotite solid solution that would dissolve and provide an ample source of copper for porphyry deposits upon melting of the amphibolite. Burnham (1981) concludes "it is unnecessary to call upon abnormally copper-rich rocks, such as the metalliferous sediments of the Nazca plate (or copper-rich Precambrian basement rocks), for the sources of ore-bearing magmas."

This argument is most convincing for the numerous deposits that lie inboard a reasonable distance (150–250 km) from present or former trenches of subduction zones. However, a rational explanation for distant relatively isolated deposits hundreds of kilometers from such trenches is more elusive. Coney and Reynolds (1977) tracked the systematic variation in the radiometric ages of Cretaceous and Tertiary igneous rocks, and concluded that the dip of the Benioff zone (subducting slab) flattened progressively beneath southwestern North America during the interval beneath 130–110 Ma and about 55–40 Ma. The decrease in dip is believed due to a high rate of convergence—the higher the rate, the lower the angle of dip. If this analysis is correct, the copper and other metals in the great porphyry deposits of Butte, Bingham, and Ely could have come from partial melting of shallow-dipping relatively fast-moving subducting slabs. Further support for this argument is that similarities in general geochemistry of intrusive rocks associated with porphyry copper deposits and style of porphyry copper mineralization in continental terranes, compared to that in island-arc terranes, suggest that the magmas in both types of terranes were probably largely derived beneath the crust, and that continental contamination contributed insignificantly to the magma or metals (Mitchell and Garson, 1981).

One further point worth noting is that, while most deposits of the porphyry type appear in general to be spatially related to a subduction zone and hence to a compressional tectonic regime, it is also evident that a high percentage of porphyry deposits are localized at or near the intersection of important fracture systems, one system commonly being strike slip, and the other extensional dip slip (Hollister, 1978; Titley, 1982). This is further borne out by the presence of abundant dikes closely associated with porphyry copper deposits, which clearly indicates an extensional environment at the time of intrusion and mineralization. The favored structural environment in which many porphyry systems were emplaced would thus appear to be tensional, at least at the level of emplacement.

TIN

Deposits of tin in the northeast quadrant of the Circum-Pacific are sparse, widely scattered, and small. The few deposits that have produced tin are widely separated localities from the Seward Peninsula in Alaska to central Mexico. Some tin has been produced as a by-product in the production of other metals, mainly from the Sullivan lead-zinc mine in southern Canada (lat 50° N.). All the deposits that have produced tin are in the craton, but unproductive occurrences of tin are present in accreted terranes as well as in the craton.

Sainsbury and Reed (1973) observe that tin deposits are typically associated with rhyolite and biotite-muscovite granite, the so-called "tin granites," and that this association is so well marked on a worldwide scale that there seems little likelihood of finding significant tin in other geologic environments. Inasmuch as such rocks are characteristic of the craton, it is obvious that exploration for new-deposit resources of tin in the northeast quadrant should focus on the craton rather than on the accreted terranes. In addition to the tin associated with base metals at the Sullivan mine, the main areas of known tin mineralization are in (1) greisen-like deposits on the Seward Peninsula, Alaska, (2) a belt containing sporadic placer deposits across central Alaska (not shown on map), (3) abundant but small veins and encrustations in rhyolitic rocks in New Mexico and in central Mexico, (4) veins in granitoid and metamorphic rocks in the southern Sierra Nevada batholith, California (Sainsbury, 1969; Cobb, 1960), and (5) small vein, skarn, and greisen deposits in the McQuentin and Cassiar districts of Yukon and British Columbia (not shown on map). As noted by Sainsbury and Reed (1973) the geology of vein tin deposits is well understood, but the genesis of tin deposits and of "tin granite" remains a field for speculation and debate.

SILVER

Silver deposits fall into two broad categories: (1) deposits in which silver is a by-product or co-product produced with other metals, and (2) deposits in which silver is the major constituent. Heyl and others (1973) observed that most of the silver produced results from by-product or co-product production, and they listed nine types of deposits having such production. Chief among these are various types of base-metal deposits. On this map only those deposits in which silver is the major constituent are shown. Essentially, this includes silver-vein and replacement-type deposits. The distribution of silver deposits is thus restricted on this map, and does not reflect the distribution of all silver-bearing deposits.

The vein and replacement deposits occur mainly in areas underlain by continental crust or the craton, but also in some areas in Canada and western United States that are underlain by accreted island-arc terranes. No silver deposits are present in oceanic crust terranes except deposits in which gold is the principal metal. The great "bonanza"-type vein deposits such as Comstock and Tonopah, Nev. in the western United States are in postaccretionary volcanic rocks. At Comstock these host rocks overlie an accreted island-arc terrane, whereas at Tonopah the host rocks overlie continental crust of the craton. Most of the silver deposits that are in postaccretionary volcanic rocks in Mexico are underlain by either craton or accreted continental crust. The giant Coeur d' Alene district deposits near lat 47° N. long 116° W. are in Precambrian cratonal rocks.

In view of the exceedingly broad distribution of silver-bearing deposits, it is difficult to speculate on the source of the metal. Silver evidently can form in a large variety of tectonic environments. As reported by Heyl and others (1973) citing Degens and Ross (1969), seafloor muds of the Red Sea contain lead, zinc, iron sulfides, and some silver in lenticular basins. These metals are being deposited by heated brines rising through the seafloor in the central part of the Red Sea. In the Salton Sea area of southern California brines tapped from a deep drill hole contain notably high concentrations of heavy metals, including silver. Polymetallic sulfide hydrothermal vents of the East Pacific Rise contain 300–5,000 g silver derived from oceanic tholeiitic volcanoes (Hekinian and others 1980). The source of the silver and other metals in the Red Sea and Salton Sea may have been a deep magmatic source, as believed by White and others (1963), or it may have been derived from leaching of evaporite beds or deltaic sediments (Craig, 1969). The uncertainty illustrates the high degree of speculation in identifying the primary source of metals in nearly any type of deposit, even those that can be observed forming today. Silver in particular, because of the extremely scattered distribution of its deposits, may have come from multiple sources.

BARITE

Deposits of commercial barite have been divided into three main types by Brobst (1973): vein and cavity filling, residual, and bedded. Only the bedded and vein-type deposits are significant in the northeast quadrant of the Circum-Pacific and they are not differentiated on the map. Bedded deposits, the most important type commercially, occur in rather well-defined arcuate belts in the cordillera from eastern Alaska southward to northern Mexico, and in Colombia, South America. No bedded deposits have been identified in the published literature from central and southern Mexico or Central America, although Reyna (1956) mentions that small barite deposits are present in nearly all parts of Mexico. Some of these may be the bedded type. Large bedded deposits are also present in the Ouachita Mountains of the south-central United States.

Most bedded barite deposits in western North America are Cambrian to Mississippian in age. However, some deposits in northern Mexico are as young as Pennsylvanian, and the Colombian deposits are in sedimentary rocks of Cretaceous age. In British Columbia and the Yukon, stratiform barite deposits hosted by cratonal Devonian and Mississippian clastic rocks and locally associated with sedimentary exhalative lead, zinc, silver, and barium deposits constitute the largest known barite resource in the cordillera. Stratabound barite-fluorite deposits in Devonian shelf carbonate rocks of the northern Canadian Rockies also constitute a significant resource (Dawson, 1983). In the western conterminous United States, large deposits of bedded barite are interlayered with radiolarian chert and shaly mudstone of Ordovician and Devonian age. The large deposits in part of the Roberts Mountains allochthon (Shawe and others 1969) have been displaced more than 80 km eastward from their depositional site. Therefore, although they reside inland from the craton boundary, they formed in accreted oceanic crust terrane. Devonian and Mississippian deposits in California are in accreted island-arc terranes. Large bedded deposits in the Ouachita Mountains are chiefly in Devonian and Mississippian dark shaley rocks (Brobst, 1973), and deposits in northern Mexico are in accreted eugeoclinal rocks ranging in age from Devonian to Early Pennsylvanian (Poole and others 1983). Smaller bedded deposits in Colombia are in Mesozoic miogeoclinal sedimentary rocks.

The association of bedded barite with turbidite clastic rocks, dark shale, and chert of deep-water origin and chiefly of middle Paleozoic age is striking. The overall map distribution indicates that in areas such as British Columbia, deposition occurred slightly inside the continental margin in elongated fault-bounded basins or grabens. The barite in base-metal districts within this region is genetically related to exhalative base-metal sulfide deposits whose source was a system of submarine hydrothermal events (Dawson and Orchond, 1982). In the western and southern United States and in Mexico, barite is found primarily in allochthonous sedimentary rocks whose protoliths perhaps originated in back-arc basins outside the continental margin. Recent seafloor investigations have proven that barite, together with other sulphate, silicate, oxide, and sulfide minerals is deposited from fault-controlled hydrothermal vents in the San Clemente fault zone near San Diego, Calif. (Lonsdale, 1979) and along the East Pacific Rise (not shown on map) (Hekinian and others 1980).

ANTIMONY

Antimony in the northeast quadrant of the Circum-Pacific occurs mainly as veins and irregular replacements in miogeoclinal sedimentary rocks and the granitic rocks that intrude them. Numerous productive vein deposits also occur in postaccretionary volcanic rocks that overlie miogeoclinal rocks. Fairly numerous but small deposits in Canada and in the western United States are in island-arc terranes. Two deposits, one in California and one in central British Columbia (not shown on map), are associated with mercury in accreted oceanic crust. The largest production has come from vein deposits in miogeoclinal rocks and postaccretionary volcanic rocks in Mexico, and from polymetallic vein deposits in Idaho (lat 45° N., long 117° W.) where antimony was a by-product in the production of base and precious metals (Miller, 1973). However, antimony is the sole metal produced from some epithermal vein deposits in Nevada (approx. lat 40° N., long 119°–116° W.) (Lawrence, 1963) and in Mexico (Reyna, 1956).

The distribution of productive antimony deposits is rather similar to deposits of tin and tungsten in that the great majority of deposits are within the craton but fairly close to its outer boundary, within the apron of miogeoclinal rocks. A discontinuous belt of antimony deposits extends from southern Mexico northward to about lat 49° N. Only a few small deposits are known in British Columbia (not shown on map). Antimony deposits in Alaska, although numerous, are all small and of little economic value (not shown on map). In the western United States the antimony belt largely overlaps the areas of tungsten and tin deposits. In Mexico, antimony seems to have no spatial relation to tungsten but lies in a discrete belt east of the main belt of tin deposits.

The narrow linear belts of antimony deposits suggest spatial relation to a subduction zone. The spatial association between antimony and tungsten and the similar style in occurrence within and parallel to the craton suggests that the source of the antimony may have been from the same magma regime as the tungsten, that is, from partial melting of a subducting slab. The antimony may have been more fugaceous or less reactive with carbonate rocks than tungsten at the deeper crustal levels, and may have moved to higher levels to form the characteristic epigenetic deposits.

PHOSPHATE

Deposits of phosphate of commercial or potentially commercial value include several types (Cathcart and Gulbrandsen, 1973), the most important of which is marine sedimentary phosphate. Large deposits of this type are located in areas of the craton overlain by miogeoclinal rocks from northern Alaska to Mexico, and in Colombia. Not all are presently of commercial grade. The age of these deposits ranges from Mississippian to Cretaceous. The largest deposits are in the Phosphoria Formation of Permian age in the western United States. Other phosphatic deposits of less economic potential occur in platform rocks of the craton, and deposits of younger (Miocene) age occur in California, Peru (not shown on map) and also in the southeastern United States.

Sedimentary phosphorite occurs in areas where divergent upwelling seawater conditions prevail. McKelvey (1963) has shown that in the late Tertiary phosphorite was deposited in warm latitudes between lats 40° N. and 40° S., mainly on the west coasts of continents; the same is true of phosphorite being deposited today. Although older deposits such as Mississippian and Triassic phosphates in northern Alaska show no such clear-cut geographic distribution, Sheldon (1964) has shown that when deposits of ancient phosphorite such as these "are located according to their virtual geomagnetic poles, their resulting paleolatitudinal distribution closely matches the latitudinal distribution of younger phosphorite." Also the paleogeographic setting of the ancient phosphorite matches the setting of younger phosphorite. Sheldon concludes that paleomagnetic and paleogeographic data can aid significantly in the search for ancient phosphorite.

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MAP 4
INFERRED FAVORABLE AREAS FOR COPPER, TIN, SILVER, BARITE, ANTIMONY, AND PHOSPHATE DEPOSITS

EXPLANATION

DEPOSIT TYPE

[Where deposit types overlap, color of smaller deposit type is shown. Boundary of larger deposit type is dotted through smaller deposit type]

- ■ **Copper**—Porphyry
- ■ **Tin**—Vein, greisen, skarn
- ■ **Silver**—Vein and replacement
- ■ **Barite**—Vein and bedded
- □ **Antimony**—Vein and replacement
- ■ **Phosphate**—Sedimentary

TERRANE TYPE

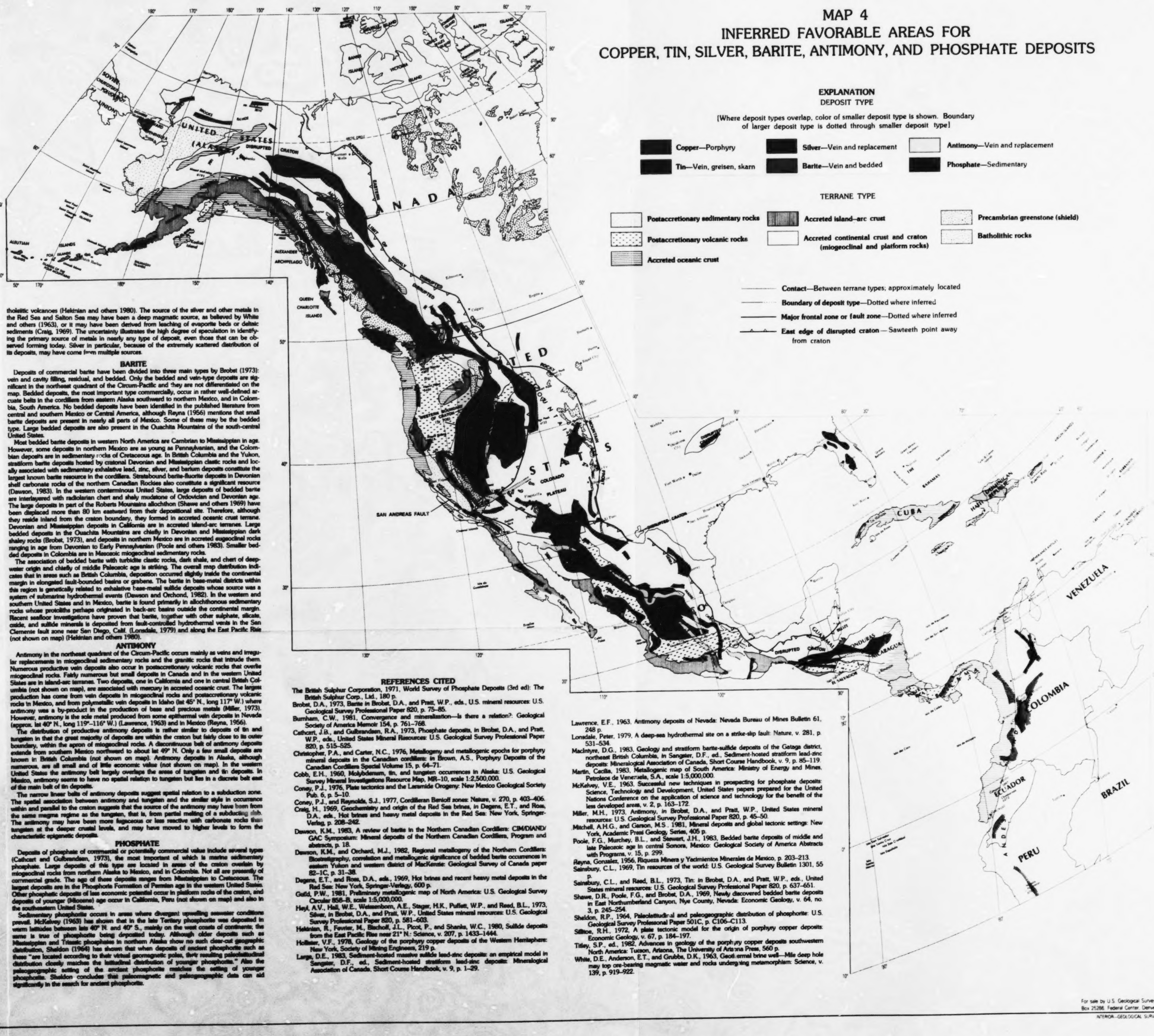
- □ **Postaccretionary sedimentary rocks**
- ▨ **Postaccretionary volcanic rocks**
- ▤ **Accreted oceanic crust**
- ▥ **Accreted island–arc crust**
- □ **Accreted continental crust and craton (miogeoclinal and platform rocks)**
- ▨ **Precambrian greenstone (shield)**
- ▨ **Batholithic rocks**

Contact—Between terrane types; approximately located

Boundary of deposit type—Dotted where inferred

Major frontal zone or fault zone—Dotted where inferred

East edge of disrupted craton—Sawteeth point away from craton



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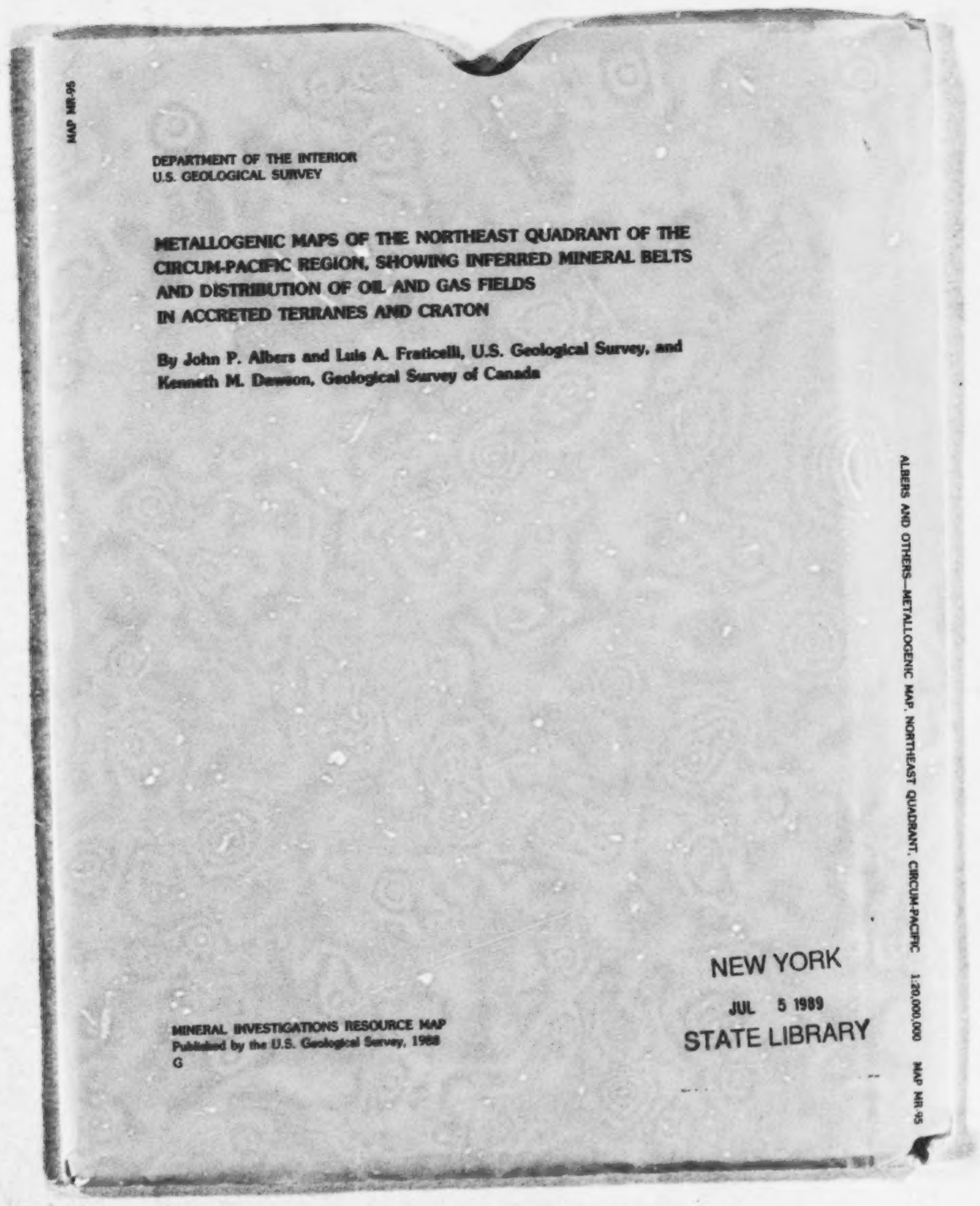

MAP MR-95

DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

METALLOGENIC MAPS OF THE NORTHEAST QUADRANT OF THE CIRCUM-PACIFIC REGION, SHOWING INFERRED MINERAL BELTS AND DISTRIBUTION OF OIL AND GAS FIELDS IN ACCRETED TERRANES AND CRATON

By John P. Albers and Luis A. Fraticelli, U.S. Geological Survey, and
Kenneth M. Dawson, Geological Survey of Canada

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